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TAMPERE UNIVERSITY OF TECHNOLOGY

NGUYEN LE TRUNG

A NEW APPROACH FOR COLLECTING DATA IN WIRELESS SENSOR NETWORK

Master of Science thesis

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ABSTRACT

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The aim of the thesis is to propose a new way for collecting distributed data in Wireless Sensor Network (WSN) which can overcome the drawbacks existed in modern Wireless Sensor Network systems. The short lifetime and large number of needed sensor nodes problems are investigated to get the major causes for those disadvantages of existed WSNs. Unmanned Aerial Vehicle (UAV) and Bluetooth Low Energy are two new technologies considered in to WSN system design for reducing the sensor node's energy consumption and decreasing number of deployed sensor nodes.

This work concentrates on analysis how WSN can be improved in the new system. First, the operations of chosen technologies for the new system are examined to show how they meet the target requirements. Second, the energy consumption for BLE single connection is examined to estimate the life time of proposed system. And finally, the number of needed nodes for the new system is calculated to compare with the required nodes in the modern systems in order to keep both systems operate normally. This is done to prove how the proposed WSN system is more efficient than modern systems.

The analysis is conducted mainly by using MATLAB software to simulate the behaviors of proposed system. The simulation focuses on two aspects: number of required nodes for covering and number of nodes for keeping the connectivity in random deployment. The number of nodes for covering the desired area is estimated by calculating the percentage of area's fractions that are not covered by any sensor. And the number of nodes for maintaining connectivity is estimated to meet the requirement that the whole network is at least 1-connected. Both calculations are using probability-based algorithm and applied in random deployment scheme.

PREFACE

This Master of Science thesis had been done under the guidance of Prof. Yevgeni Koucheryavy and Dr. Dmitri Moltchanov in the Department of Electronics and Communication Engineering in Tampere University of Technology, Tampere, Finland from November 2014 to April 2015.

First of all, I would like to thank Prof. Yevgeni Koucheryavy for giving me the opportunity to be under his guidance. My research have gone this far due to his moral support and guidance.

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Tampere, 2015

Nguyen Le Trung

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LIST OF ABBREVIATIONS AND SYMBOLS

API	Application Programming Interface
ATT	Attribute Protocol
BER	Bit Error Rate
BLE	Bluetooth Low Energy
BR/EDR	Classic Bluetooth
C1WSNs	Category 1 WSNs
C2WSNs	Category 2 WSNs
CMT	Cable Mode Transition
DDD	Dull, dirty, dangerous
FSPL	Free Space Path Lost
GAP	Generic Access Profile
GATT	Generic Attribute Profile
GCS	Ground Controller Station
GPS	Global Positioning System
GSM	Global System for Mobile
HCI	Host Controller Interface
IC	Integrated Circuit
ICAO	International Civil Aviation Organization
IoT	Internet of Thing
IrDA	Infrared Data Association
L2CAP	Logical Link Control and Adaptation Protocol
LL	Link Layer
LOS	Line-of-Sight
LR-WPAN	Low-Rate Wireless Personal Area Network
LTE	Long-Term Evolution
MAC	Medium Access Control
NFC	Near Field Communication
PHY	Physical
RC	Radio Control
RFID	Radio Frequency Identification
RWP	Random Waypoint Mobility
SM	Security Manager
SoC	System on Chip
TUT	Tampere University of Technology
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle

WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

$A_0(F_0, L_0)$	Monitoring area
$A_i(F_i, L_i)$	Node sensing area
d	Distance between transmitter and receiver $[km]$
d_a	Time to send advertising package $[s]$
d_{IFS}	interframe-space $[s]$
d_t	Connection interval $[ms]$
d_{tw}	transmitWindow $[s]$
d_{two}	transmitWindowOffset $[s]$
E	Energy $[J]$
F_0	Area of monitoring area $[km_2]$
F_i	Area of node sensing area $[km^2]$
f	Carrier frequency $[MHz]$
G_r	Receiver antenna gain $[dBi]$
G_t	Transmitter antenna gain $[dBi]$
h	UAV relative flying height $[m]$
I	Current $[mA]$
L_0	Perimeter of monitoring area $[m]$
L_i	Perimeter of node sensing area $[m]$
M	Number of *sub-nodes* in monitoring area $[nodes]$
N	Number of *sink-nodes* in monitoring area $[nodes]$
P	Power $[W]$
P_{ad}	Power consumption of *advertising event* $[mW]$
P_{con}	Power consumption of *connection event* $[mW]$
P_r	Receiver power transmission $[dBm]$
P_t	Transmitter power transmission $[dBm]$
R	BLE communication range $[m]$
T	Connection duration $[s]$
T_a	Advertising interval $[s]$
$T_{a,0}$	Static advertising interval $[s]$
T_{con}	Connection time $[s]$
T_{dis}	Discovering time $[s]$
T_f	Life time of routing WSN $[s]$
T_s	Scanning interval $[s]$
t	Time $[s]$
t_c	Connection time $[ms]$

U	Voltage $[V]$
v	UAV flying speed $[m/s]$
ρ	Random time added to advertising interval $[s]$

1. INTRODUCTION

Communication technologies has changed tremendously over the past few decades from wired network (e.g. Ethernet, optical network) to wireless network (e.g. WiFi, Cellular network), from centralized network to decentralized network (e.g. peer-to-peer network). Along with the improvement and appearance of new communication techniques, the combination of multiple fields also provide considerable contribution in this change. In this scheme, Wireless Sensor Network (WSN) emerges as the convergence of the Internet, communications and information technologies, coupled with technological advances in sensor technologies. This aggregation opens a door for a new low-cost sensor generation which is capable of a high-level spatial distribution. It is a leap in monitoring and controlling activities not only in military area but also in industrial and civil fields.

Wireless Sensor Network can be described as a network of tiny devices with low power consumption, years of operation, but limited computation, communication and memory. These characteristics open opportunities for new applications. However, there are some constraints in designing and operating WSN. Most of researches now focus on energy efficient designs, algorithms and protocols. For example, a Cable Mode Transition (CMT) algorithm was proposed to determine the minimal number of active sensor nodes in order to maintain K-coverage of monitoring terrain as well as K-connectivity of the network [15].

In general, sensor networking is a multi-area domain including radio, networking, signal processing, database management, resource optimization, power management, platform technology (hardware and software), etc. The applications, networking principles, algorithms, and protocols for Wireless Sensor Network are in process of development. However, with upcoming advances in sensors and communication technologies, Wireless Sensor Network is still a potential technology for collecting environmental data and an essential component of Internet of Things (IoT).

1.1 Wireless Sensor Network (WSN)

1.1.1 WSN overview

Wireless Sensor Network (WSN) is a network of spatial distributed autonomous sensors to monitor physical or environmental parameters and cooperatively transfer data to main server. Monitored parameters depend on the functions of sensor node in network such as physical sensors (e.g. temperature, moisture, radio-wave frequency sensors), chemical sensors (e.g. dissolved oxygen, electrical conductivity, pH sensor), biological sensors (e.g. microorganisms sensor), national security oriented sensors and many other newly invented sensors [18]. Nowadays, sensor is not only a single element but also equipped with multiple on-board sensing elements called sensor node.

A WSN usually has two main parts: (1) sensing system to generate and collect distributed sensor values; (2) data processing and storage system to process and locally store sensor values before forwarding to user (Fig. 1.1).

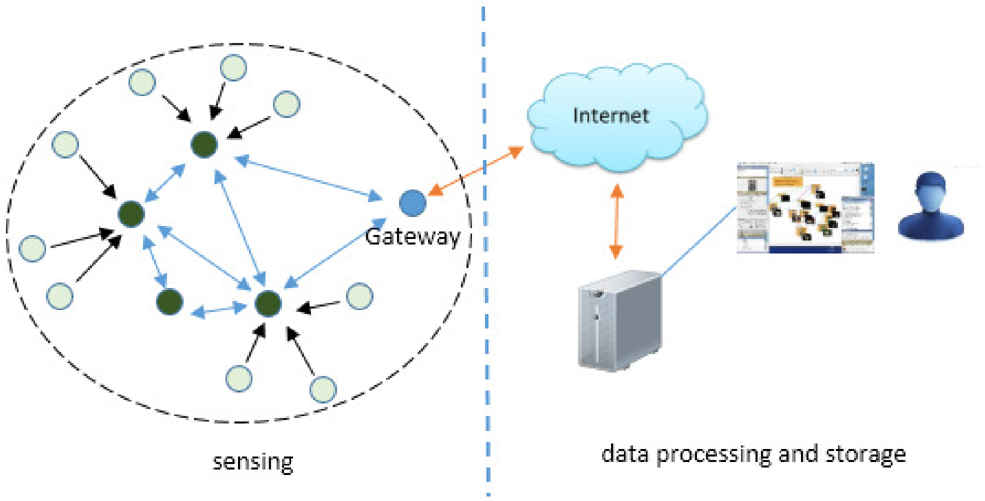


Figure 1.1 *Wireless Sensor Network's components.*

- *sensing system (sensor network)*: composed by hundred of self-organizing sensor nodes which communicate among each other by radio signal and form an ad hoc like network. These sensors are a small units having limited storage capacity, processing speed and radio bandwidth. Sensor nodes can be manually or randomly deployed and can cover a large area with high density depending on application requirements.

- *data processing and storage system*: can be a normal server which stores sensor values and translates it into readable value for user.

Normally, a WSN is deployed for a specific task (environment monitoring, target tracking, etc.) and designed to optimize performance base on deployment scenario. Sensor values can be transferred from sensing system to processing server via the Internet or local network and preprocessed by sensing system to optimized network performance. Moreover, server provide a user interface, management and control services to users.

There are many types of devices and sensor nodes in WSN to keep the network works and has a good performance. They are categorized in 4 basic types based on functional and communicative roles.

- *Sub-node (leave node, end device)*: node without routing. This node can only sample physical or environmental data from monitored environment and transfer its own data to other nodes.
- *Head-node (router node)*: node which can receive data from other node and forward it to *sink-node*. Depending on network design *head-node* itself can be a normal node to collect data or just works as a routing point.
- *Sink-node (gateway)*: node which collects or requests data from other nodes and forwards data to another network. *Sink-node* can be a normal router node except it will not forward data to other nodes in network.
- *Controller (coordinator)*: a central controller entity to coordinate node addressing and joining network, instruct routing, schedule transmission, synchronize between nodes, etc. Depending on network design, WSN system can work with or without this element.

Depending on the application tasks and requirements, a WSN can contain all these types of nodes or some of them. Since sensor node is integrated from many elements, it can play more than one role in WSN.

1.1.2 Topology and protocol stack

WSN is an application oriented technology. Choosing and maintaining a proper network topology play important roles in improving network performance. It can be point-to-point (peer-to-peer), star, mesh, hybrid or tree topology depending on the aim of application and supports from communication technology used in network. A matching topology will enhance network performance in energy efficiency, bandwidth utilization, network deployment or event deployment cost. Generally, WSN topologies can be categorized in *flat* topology and *clustered* topology (Fig. 1.2).

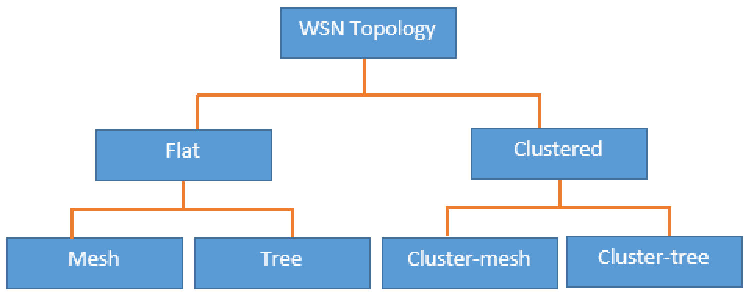


Figure 1.2 *Clustered topology.*

- *Flat topology*: a node is capable to route its data toward server by itself, all nodes are equal and play the same role in network. Each node can maintain connectivity with any nodes within the range by itself. Flat topology can be tree, mesh (peer-to-peer) topology or their combination (Fig. 1.3).

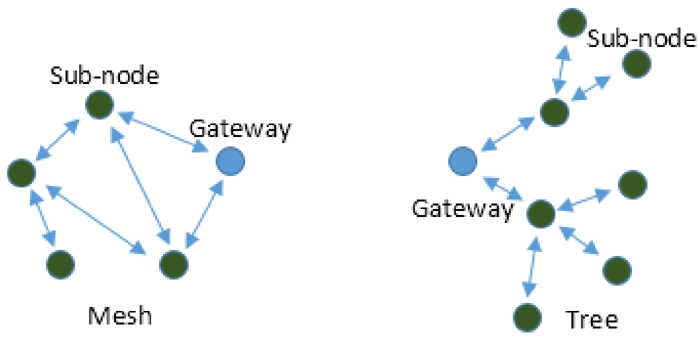


Figure 1.3 *Flat topology.*

- *Clustered topology*: only a subset of nodes (*head-nodes*) can route data among each others and the rest will provide data only to routing node which they are connected to. Network is divided usually based on the geographical position of nodes. Nodes close together might be grouped in a cluster. Topology between clusters can be mesh (*cluster-mesh*), tree (*cluster-tree*) or their combination (Fig. 1.4).

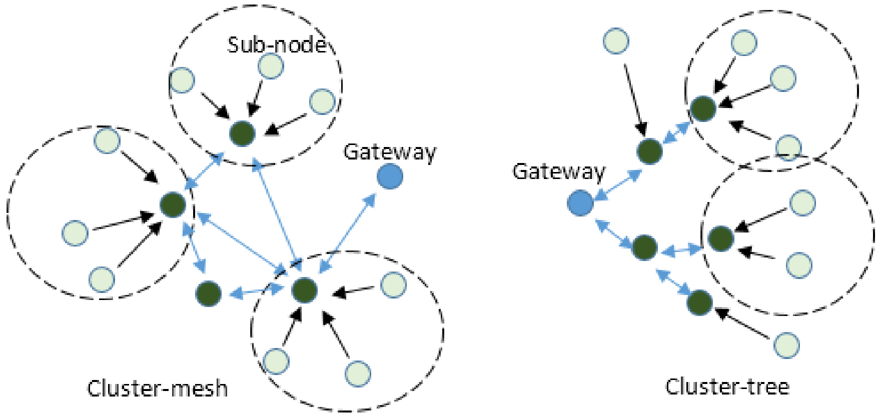


Figure 1.4 *Clustered topology.*

Clustering in network will make network become hierarchical and also improve the bandwidth utilization because only some dedicated nodes maintain connection on communication channels. In stationary WSN, *cluster-tree* toplogy has the best energy efficiency while *cluster-mesh* topology provides the maximum robustness which allows multi-path routing and multiple sinks.

Another aspect which has high influence in WNS performance is the protocol stack. The WSN protocol stack is like the traditional protocol stack with the following layers: Application, Middleware, Routing, Data Link, and Physical (Fig. 1.5) [18].

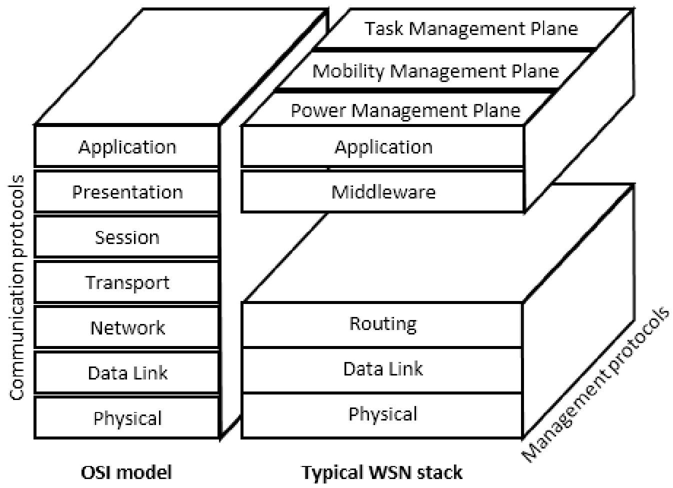


Figure 1.5 *WSN protocol stack.*

In WSN communication protocol stack, the application protocol is responsible for consuming/producing data while routing protocol decides what to send and whom to send. The transport layer is combined into application layer and is responsible for reliable data delivery required by the application layer. The data link layer is responsible for data stream multiplexing, data frame creation and detection, medium access, and error control in order to provide reliable point-to-point and point-to-multipoint transmissions. In WSN data link, MAC plays an important role to distribute shared medium or communication resource fairly and efficiently. A well designed MAC protocol will help to archive good network performance in term of energy consumption, network throughput, and delivery latency. Physical layer is in charge of converting bit streams from the data link layer to suitable signals which is transmittable over the communication medium.

In combination with communication protocols, management protocols are applied in WSN protocol stack. The power management plane manages how a sensor node uses its power, minimizes the power consumption and may turn off some node functions to preserve energy. The mobility management plane detects and registers the movement/mobility of sensor nodes so that nodes can keep track of their neighbors and maintain a data route to the sink. The task management plane balances and schedules the events' sensing and detecting tasks so only necessary nodes are assigned to sensing tasks while the rest can focus their energy on routing and data aggregation [1].

Designing efficient, reliable communication protocols for WSN is quite challenging due to the uncertainty and dynamic of monitoring environment. Although WSN is ad hoc-like network but it is still different from traditional ad hoc network in a few ways. The protocol stacks have to be designed to minimize power consumption and preserve network lifetime. Since sensor nodes do not have global ID, the protocols have to handle with attribute-based naming and clustering. Also WSN protocol stack has to deal with specific type of information, data-centric routing and data aggregation coming from sensing area. And the last problem is sensor nodes' positions may not be predetermined when deploying. This requires routing protocol to have the capability of providing self-organized routes.

1.1.3 Gathering distributed data in WSN

Although a sensor can be self-operate and independent from network, it still has limitation in power consumption, memory capacity and processing speed. Typically, sensor values will be collected and processed outside sensor network. All other applications located outside will connect to sensor network via gateway device (Fig. 1.1).

There are two ways to collect sensor values in WSN. *Single-hop* based approach and *multi-hop* based approach [18] (Fig. 1.6).

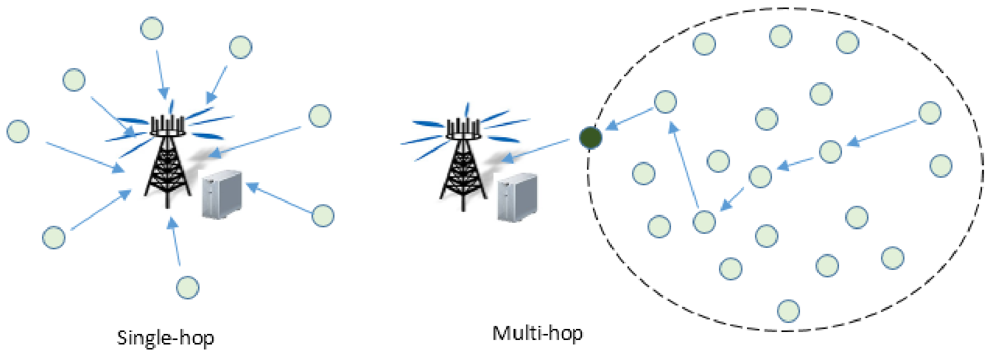


Figure 1.6 *Ways to collect WSN data.*

In single-hop approach, sensor node simply transfer data directly to base station (or gateway). However, it will cost energy when nodes stay far away from base station or nodes are mobile and move away from base station. *Multi-hop* approach can address the shortcoming of the single-hop approach by relaying data packet between source and destination using intermediate nodes (routing nodes). During data transfer operation, intermediate nodes can also aggregate data to gain power efficiency.

In multi-hop approach, data are transferred based on three different routing strategies: *proactive*, *reactive*, and *hybrid* [18].

- *Proactive routing (table driven)*: routing information is disseminated periodically to maintain an accurate routing table across all network's nodes. This strategy can be applied to both flat and clustered topology. Flat topology has high potential to compute optimal path.
- *Reactive routing*: establishes the routing path on demand and does not maintain the global routing information on nodes. The routing path to a specific destination will be searched when requested. Routing path is dynamic and usually discovered by flooding node's information then built based on replying packets. This routing strategy is suitable with network which usually has changes in deployment.
- *Hybrid routing*: depends on network structure. Hybrid routing can be applied on clustered network with proactive routing used within a cluster and reactive routing used across clusters.

Usually, a built in routing protocol is used to spread sensor values within WNS in multi-hop approach. This routing protocol can be either *sender-decided* or *receiver-decided* package forwarding protocol [9].

- *Sender-decided forwarding protocol*: sender sends packets to the chosen known neighbors and packets can be routed on the shortest path. This routing protocol shows better power consumption performance.

- *Receiver-decided forwarding protocol*: sender broadcasts packets to all neighbors and neighbors will determine whether to forward or discard packets to avoid loop and collision in routing. In this case, nodes don not have to know about their neighbors therefore they can save memory used for routing information.

1.1.4 WSN applications

Fundamentally, WSN application only provides two major services: sensing service (or monitoring service) and controlling service. However, WSN supports a broad spectrum of applications: military applications, environmental applications, health care applications, civil applications, industrial applications and many more.

Commercial WSNs can be classified into two categories [18]:

- *Category 1 WSNs (C1WSNs)*: almost invariably mesh-based network with multi-hop radio connectivity among or between nodes, utilizing dynamic routing in both the wireless and wire portions of the network [18].

- *Category 2 WSNs (C2WSNs)*: point-to-point or multi-point-to-point (star-based) systems generally with single-hop radio connectivity to WNs, utilizing static routing over the wireless network. Usually, there will be only one route from the nodes to the companion terrestrial forwarding node [18].

Nowadays, most of WSN applications are C1WSNs in which sensor nodes are distributed in large sensing area and form a mesh-based network for better data collection and provide back up in case of node failure. Furthermore, modern WSNs are multi-tasking systems which provide many services (monitoring, controlling, positioning, measuring, etc) at the same time. They can be either one sensing system with multi-purpose sensor nodes or multiple single-task sensing systems connect to one data processing and storage system. Heterogeneous data are integrated in metadata and can be accessed by any authorized individual from website or mobile application via Internet (Fig. 1.7). In some WSNs, redundant data and unused information from sensor node can be removed to reduce communication cost.

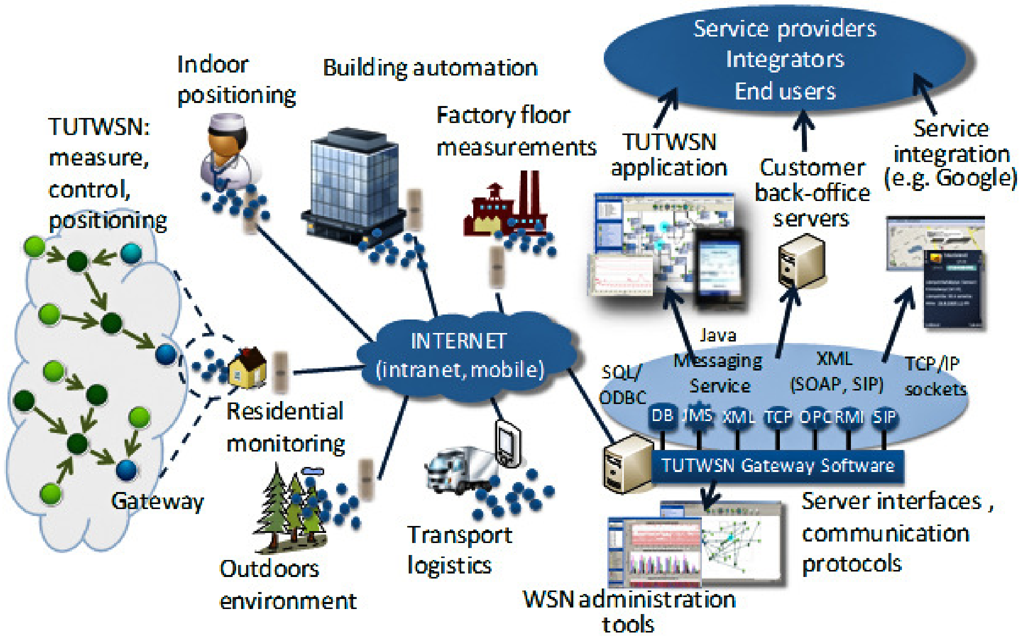


Figure 1.7 *Tampere University of Technology WSN.*

1.2 New approach for collecting data in WSN

1.2.1 WSN issues

Although WSN have been applied widely in many areas, there are still some considerable drawbacks that prevent it not to become the first technological choice in many cases. Two major shortcomings that mostly effect WSN are power consumption and large redundant nodes requirement to maintain network operation and performance.

WSNs are usually deployed for sensing or monitoring in a long duration (months or years) which change or replace power supply (battery) for hundreds of sensor devices is not feasible. Therefore, network power consumption is one of the constrains should be considered when designing WSN. The less energy used, the more lifetime system has. The power consumption of WSN can be effected by power consumption of individual node, node's life cycle, network topology or routing protocol.

To operate effectively, sensor node has to sleep 90% of working time (Fig. 1.8) and only wakes up in schedule or by activation . Most of node's energy is consumed during active time. Therefore a proper sleeping interval can keep sensor node works for long time duration. In single-hop based WSNs (star topology) where node communicates directly with base station, sleeping interval only depends on application requirements. Meanwhile in multi-hop based WSNs (mesh, tree, clustered topology)

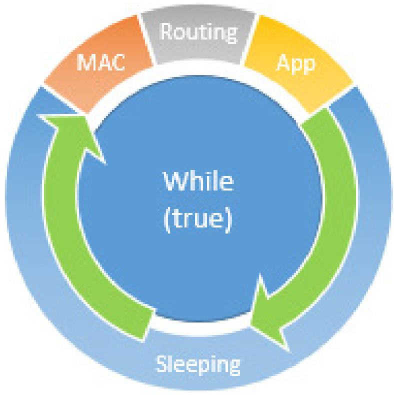


Figure 1.8 WSN node duty cycle.

where sensor data is routed toward gateway node, the intermediate nodes which forward data have to be more active. Particularly, nodes at the edge of sensing field and connect to gateway or *sink-node*, they have to handle traffic from all nodes in cluster which make them drain out of battery quickly. Some techniques are developed to enhance the power efficiency of node. For instance, data aggregating technique can reduce the data transfer on intermediate node but lead to high latency and inaccurate data.

Another issue of WSN is the number of required nodes needed to keep good network performance are quite huge. When deploying WSN, nodes will be setup to cover all monitoring area . At the same time, they have to keep connectivity with other nodes to exchange data. Usually, the number of required nodes to keep connectivity is larger than number of required node to keep coverage. This number can goes to thousands of nodes for keeping connectivity in comparison with hundreds of node needed for coverage.

1.2.2 Proposal for new WSN system

Due to existing issues of WSN, this thesis work proposes a new WSN system to overcome the drawbacks of WSN by using Unmanned Aerial Vehicle (UAV) to collect distributed data in combine with Bluetooth Low Energy (BLE) communication technology. New system is designed based on the idea: instead of keeping *sink-node* stationary and waiting for data by routing, we make it mobile to collect data and apply new low energy technology which was not designed for WSN to reduce power consumption.

Several solutions in combining UAV with WSN to enhance WSN performance was proposed such as using UAV to interconnect between sparse clusters located at fragmented parcels and a base station [22], using a cooperative connected UAVs as *sink-nodes* to collect data in clusters, [23], using UAV as a mobile node in WSN for emergency situation, or using UAV as an addition solution for charging, deploying WSN nodes [12] [20]. This thesis solution will consider using UAV in WSN as a mobile *sink-node* to connect sensor network part with processing part. Also, a low-power solution developed for Wireless Personal Area Network (WPAN) is applied as a mean of communication (Fig. 1.9).

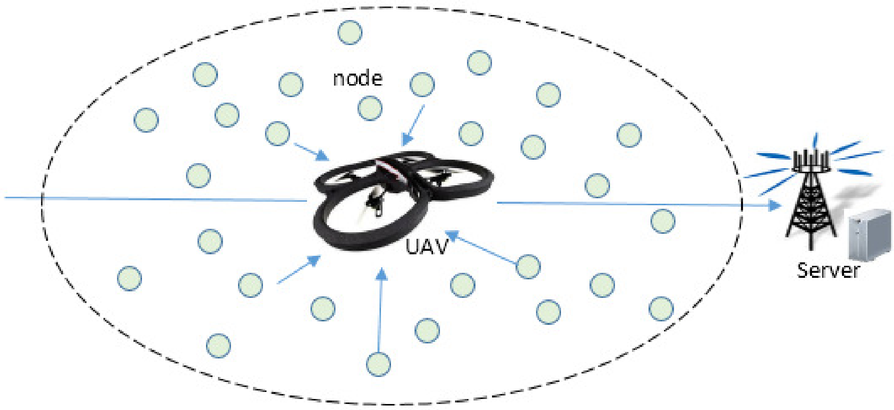


Figure 1.9 *Proposed WSN.*

The proposed WSN system is designed based on single-hop data transmission approach where a UAV carries a *sink-node* and fly through monitoring area to collect data from deployed sensor nodes connected to it. Sensor nodes and *sink-node* will communicate with each other using BLE. *Sink-node* can either send a wake up signal continuously to activate sensor node to get data or scan for periodical wake up sensor nodes to establish connections and exchange data. After data collection process, UAV can come back to base station for transferring collected data to server and recharging battery. New system is designed for UAV to collect sensor data in schedule or anytime when needed. UAV also can be programmed to monitor the whole sensing area or a part of it.

There are some advantages can be pointed out from the new design. Firstly, the *sink-node* node mobile and sensor node is stationary will make sensor node consume less energy. Secondly, sensor nodes do not have to spend energy on keeping connectivity with other nodes, also energy for routing schedule is reduced. Finally, new system only needs a number of node to cover deploying network and don not have to worry about maintaining the connectivity among nodes. This will help to decrease the number of deployed nodes in monitoring area.

To illustrate how proposed system can overcome WSN issues, analyses on system operation and comparison with other WSNs are made based on technology specifications, published statistics and network simulations. The comparisons are made according to the following aspects: network lifetime, number of covering nodes, number of connecting nodes. These are the major issues appear in modern WSN systems.

The aim of proposed system is for monitoring crop fields in agriculture. Sensor nodes are spread in large crop field to monitor environmental parameters such as soil moisture, temperature, humidity, etc. Since crop fields don not required instant data tracking, UAV can fly in schedule to collect data then user can decides what to do for changing field conditions based on collected data. Further more, new WSN system can be applied for sensing environmental parameters in other areas in which network operation is limited such as river, woods, etc.

2. TECHNOLOGICAL CHOICES

In proposed WSN system, two key technologies are Unmanned Aerial Vehicle (UAV) and Bluetooth Low Energy (BLE). The goal of this combination is to take advantage from these technologies' main features: monitoring and low-power which can adapt with WSN requirements. To clarify the reasons why these technologies should become the chosen ones for new WSN system, this section will go deeper to examine how these technologies compete with other technologies in general comparisons.

2.1 UAV technology

2.1.1 What is UAV

Unnamed Aerial Vehicle or Unpiloted Aerial Vehicle (UAV) also known as drone by the International Civil Aviation Organization (ICAO), is an aircraft that is equipped with essential data processing units, sensors, automatic controller, communication systems and is capable of performing autonomous flight missions without the interference of a human pilot [3]. ICAO classify UAV into 2 categories:

- *Autonomous aircraft*: currently considered unsuitable for regulation due to legal and liability issues.
- *Remotely piloted aircraft*: subject to civil regulation under ICAO and under the relevant national aviation authority.

Although UAVs is different in size, payload and design, they share common components (Fig. 2.1) [3].

- *RC aircraft*: radio-controlled aircraft.
- *Avionic system*: collecting in-flight data, performing automatic control laws, executing mission-oriented tasks, and communicating with the ground station.

- *Manual control*: consisting of a pilot and a wireless joystick.
- *Ground station*: monitoring the flight states of the UAV and communicating with the avionic system.

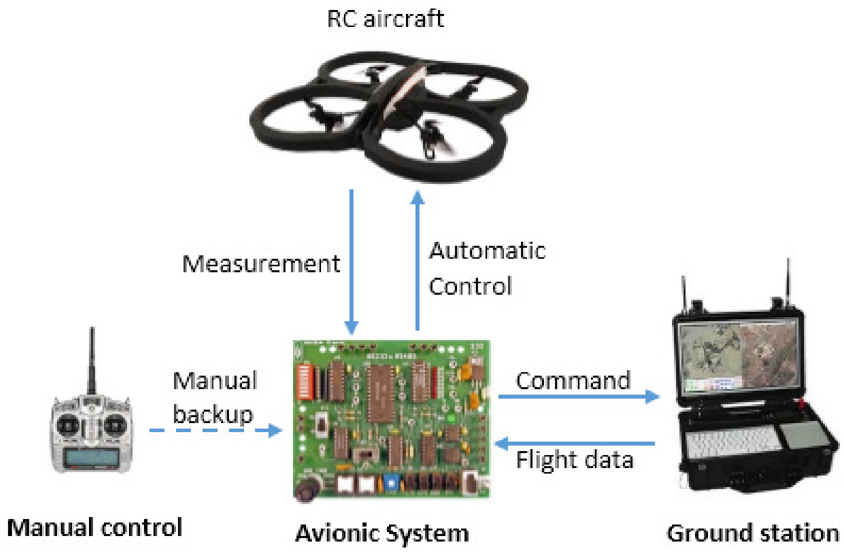


Figure 2.1 *A general UAV system.*

For small Unmanned Aerial System (UAS), there are 4 basic communication architectures to connect UAV with ground station: direct link, satellite, cellular and mesh (Fig. 2.2) [21] [21]

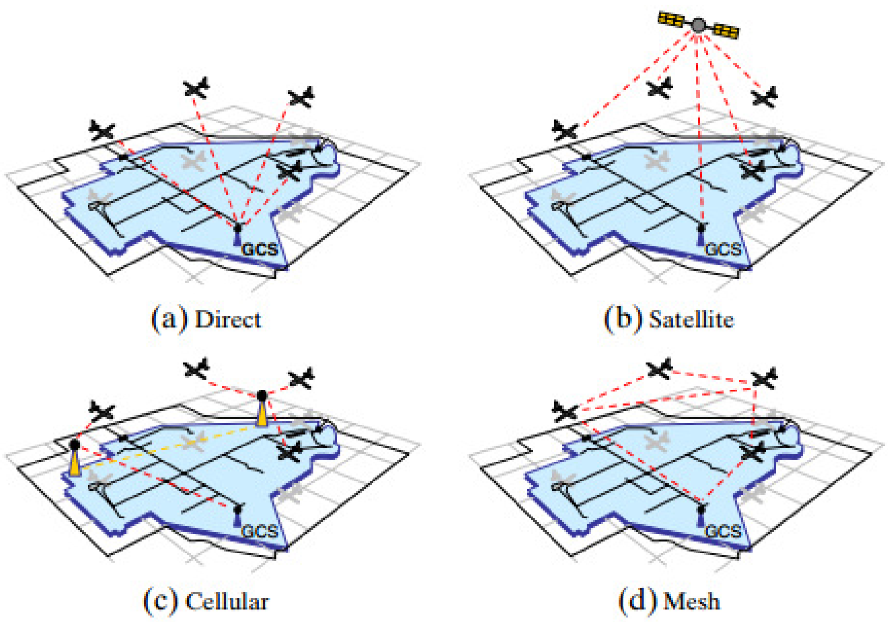


Figure 2.2 *Small UAS communication architecture*

- *direct link*: UAV connects directly to ground station on a dedicated link (channel). This is a reliable way with low latency but requires line-of-sight communication, high power transmitter in a wide range and the bandwidth varies with the number of UAVs. Direct link architecture is not a suitable option for dynamic and non-line-of-sight environment.
- *satellite*: routing, control, and data is exchanged between Ground Controller Station (GCS) and UAVs via satellite. The UAS network can remain well connected and also provide a wide coverage range. Satellite communication architecture is limited by the satellite bandwidth and high delay in operation.
- *cellular*: have many advantages such as wide coverage area, UAV handover through cellular base stations, bandwidth reuse and shared infrastructure within different UAVs. However, modern cellular base stations are not designed for flying aircraft, therefore this communication architecture require a dedicated cellular infrastructure.
- *meshing*: data can be relayed between UAV nodes but this require the appearance of intermediate nodes and order in moving to support communication.

UAV was first developed for military special operations which are dull, dirty or dangerous (DDD) such as monitoring battle field, missile decoy, monitoring radioactive area, etc [2]. Then UAV becomes more popular because of its benefits in civilian uses. And nowadays, UAV can be used for covert role (policing and firefighting), research role (airborne testing, power and pipeline measurement), environmentally critical role (disaster alert, pollution monitoring) or economic reason (crop monitoring) [2].

2.1.2 UAV for WSN

So far, UAV has been applied in many military, industrial and civil application. However, using commercial UAV in WSN is still being developed and needs to be examined. In proposed WSN system, UAV will carry BLE *master* device and flight over sensing area to collect environmental data. The aim of new system is to support agriculture in monitoring environmental parameters on large fields or planing areas where implementing sensor network connection are complicated and costly.

To examine if commercial UAV is capable to adapt with proposed application, this section will consider some of the most popular drones (DJI Phantom 2 - Fig. 2.3, Ardrone2, Draganflyer X6, etc) as the references to get the general features and abilities of drone. From producer data sheet, some drone's basic parameters and technologies are listed below:

Figure 2.3 *DJI Phantom 2 drone.*

- **Weight** 1kg - 4kg.
- **Diameter** 0.3m - 1m.
- **Operating frequency**: 2.4GHz (world wide) or 5.8GHz.
- **Communication Distance**: up to 1km with remote controller in open area.
- **Flying speed**: 0m/s - 15m/s (0km/h - 54km/h).
- **Maximum altitude**: up to 2438m,
- **Ascent/Descent speed**: 2m/s - 8m/s,
- **Payload** up to 6.5kg
- **Flying time** 30mins - 88mins (battery supply),
- **Additional features**:
  - GPS (Global Positioning System),
  - Collision protection,
  - Home landing: comeback to predefined point when UAV is losing control or automatically landing when UAV is out of battery.
  - Programmable flying route.

With available features, UAV can work well on flat area with proper flying speed and height. One option for communication architecture in this case is using cellular for controlling (Fig. 2.4). Since most UAVs are all equipped with GPS device and programmable, they can operate automatically and base station only plays a minor role for tracking or manual controlling. In auto mode, the UAV can be configured following a predetermined route to collect sensors' data then come back to base station to transfer data and recharge battery. A group of cooperative UAVs can be used in combination with a single base station or adjacent base stations to collect sensors' data in one sensing area or in different distributed sensing areas.

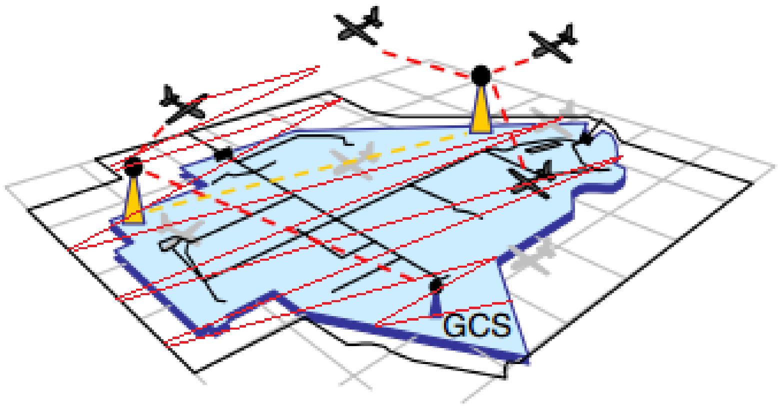


***Figure** 2.4 Cellular communication architecture.*

With maximum flying speed is 15m/s (54km/h) and working time 30 - 88 mins. A UAV can fly continuously from 27km to 79.2km. Assume that, an UAV carry BLE *master* device with communication range is around 50 - 100m, flies in zig-zag way to scan sensors on monitoring area (Fig. 2.4), the coverage area of UAV in a single flight is around 5.5256 - 15.9656km^2. This number can be extended when we optimize UAV flying route based on the distributed data of sensors collected from the first flight. In addition, UAV can also support to deploy sensor nodes by spreading these nodes from UAV itself.

It can be seen from UAV's features that UAV technology is feasible in proposed system with proper setup and design. In crop field area, which is flat and less obstacles, UAV can work at flying height above trees height (around $10 - 25m$).

2.2 Bluetooth Low Energy (BLE)

2.2.1 BLE overview

Bluetooth Low Energy (Bluetooth LE, BLE or Bluetooth Smart) is a young standard extended from conventional Bluetooth standard which was introduced with the version 4.0 in June 2010 [7]. It is a wireless personal area network (WPAN) technology designed for application in the health care, fitness, beacons, security, and home entertainment industries. BLE aims at providing a considerably reduced power consumption and cost while maintaining the same communication range in comparison with Bluetooth.

The first update for BLE is version 4.1 published in December 2013 [7] and recently version 4.2 in December 2014. Although BLE is a young standard, the world has witnessed a rapid growth in BLE's applications in smart phones, tablet and mobile computing. This can be explained easily due to many benefits converged around BLE.

What makes BLE different is it makes high demanding task accessible with a relatively modest budget. An all-in-one radio-plus-micro-controller (system-on-chip) solution can be purchased with $2 per chip in low volumes and this price is well under the price of other wireless technologies like WiFi, GSM, Zigbee, etc. Another contributed feature of BLE is that it is designed for an extensible framework to exchange data and low-level API for mobile application developers to use the BLE framework freely in any way they see fit. And finally, low-power consumption of BLE can help to solve the low battery problem in handset effectively.

In the table below is the specification of BLE published by Bluetooth Special Interest Group Table 2.1 [14] [7] in comparison with classical Bluetooth technology.

As seen in BLE specification, the new standard decreases power consumption by reducing communication channel from 80 channels in Bluetooth to 40 channels [14]. Also the peak current consumption drops by half to less than 15mA which means BLE devices can be supported by small coin-cell battery. One remarkable change in BLE is the reduction in duty cycle. Small package size support (41 bytes - Fig. 2.5 -9 times smaller than 358 bytes of Bluetooth [5]) leads to very short 376 μs package length [5]. This is the major reason keep the BLE devices less active or the active time is shorter than normal Bluetooth devices. However, to achive low energy consumption in BLE, lower bit rate and throughput is taken as the trade off.

Fundamentally, every BLE device is composed from three main protocol layers:

Table 2.1 BLE specification.

Parameter	Basic Bluetooth	Bluetooth Low Energy
RF Channels	f = 2402+kMHz	f = 2402+2kMHz
Number of channels	k = 0,1,..,78	k = 0,1,..,39
Carrier frequency tolerance	± 75 kHz	± 150 kHz
Adjacent channel (2 MHz)	−20 dBm	−20 dBm
Co-channel	11 dB	21 dB
Longest package length	3.1 ms	376 μs
Modulation type	GFSK	GFSK
Spreading technique	FHSS	FHSS
Required sensitivity	−90 dBm	−87 to −93 dBm
Transmit power	20/4/0(Class 1/2/3) dBm	−20 to 10 dBm
MAC mechanism	TDMA	TDMA
Message size	358 (maximum)	8 to 47 bytes
Error control	24-bit CRC & ACKs	24-bit CRC & ACKs
Data rate	1-3 Mb/s	1 Mb/s
Application throughput	0.7-2.1 Mb/s	0.27 Mb/s
Latency (non-connected state)	100 ms	6 ms
Minimum time to send data	<100 ms	<3 ms
Voice capable	yes	no
Network topology	Scatternet	Scatternet
Power consumption	1 W	0.01 to 0.5 W
Distance/Range	30 m	30 - 100 m (max 150 m)
Peak current consumption	<30 mA	<15 mA

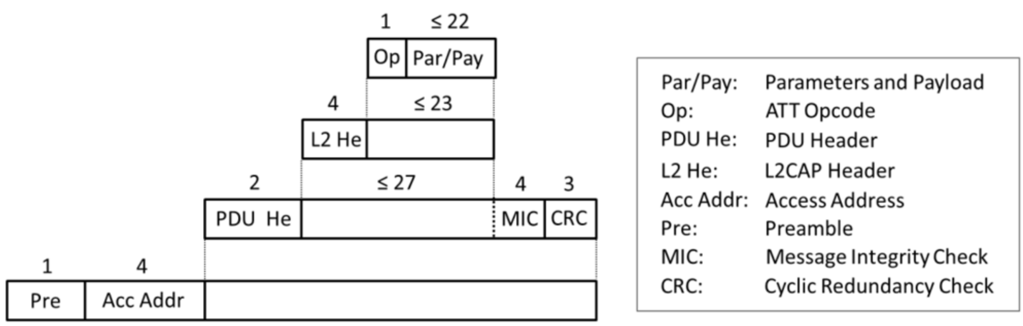


Figure 2.5 *BLE data unit structure.*

application, host and controller (Fig. 2.6) [7].

Application: the highest layer responses for user interface and data handling. Application architecture depends on implementation requirements.

Host: includes following layers:

- *Generic Access Profile (GAP)* defines how BLE devices interact with each other in lower layers.

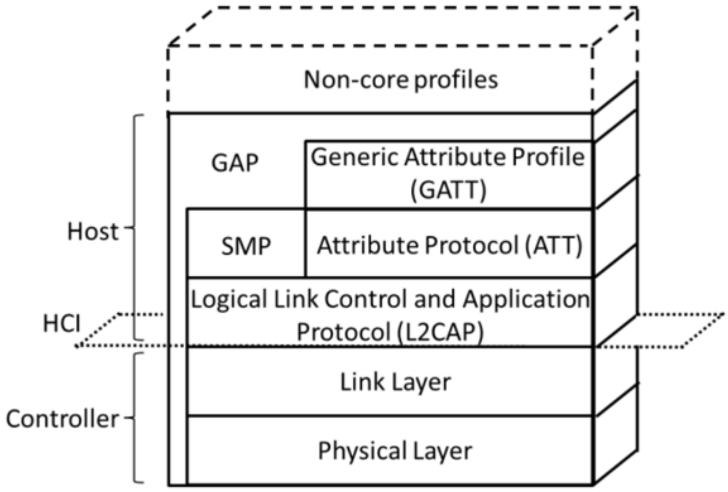


Figure 2.6 *BLE protocol stack.*

- *Generic Attribute Profile (GATT)* defines how data is organized and exchanged between applications.
- *Logical Link Control and Adaptation Protocol (L2CAP)* operates as a protocol multiplexer which encapsulates multiple protocols in BLE package and performs package fragmentation and combination.
- *Attribute Protocol (ATT)* is a simple client/server stateless protocol based on attributes presented by a device.
- *Security Manager (SM)* is a protocol and series of algorithm for BLE to exchange security keys and encrypted data.
- *Host Controller Interface (HCI), Host side* a standard protocol allows host and a controller to communicate across a serial interface.

Controller include following layers:

- *Host Controller Interface (HCI), Controller side*
- *Link Layer (LL)* interface to communicate with Physical Layer which defines *advertiser, scanner, master* and *slave* roles.
- *Physical Layer (PHY)* in charge of analog communication, modulating and demodulating, transforming analog signals into digital symbols.

Although BLE is modified from Bluetooth and they have similar protocol stack structure, these two wireless communications are incompatible. In other words, BLE devices and Bluetooth devices can not communicate directly with each other due to the differences in the on-air protocol, the upper protocol layers, and the applications. For this reason, in market today, there are three main types of Bluetooth devices (Fig. 2.7) [7]: BR/EDR device for classic Bluetooth, Single-mode BLE (Bluetooth Smart) device only for BLE and Dual-mode (BR/EDR/LE, Bluetooth Smart Ready) device which can communicate to both of them. Since classical Bluetooth has been applied for years and setup on million of devices, BLE dual mode is preferred to use on handset devices so that they communicate for both and can be used for multi-purpose. The single mode device is utilized mostly for WPAN applications.

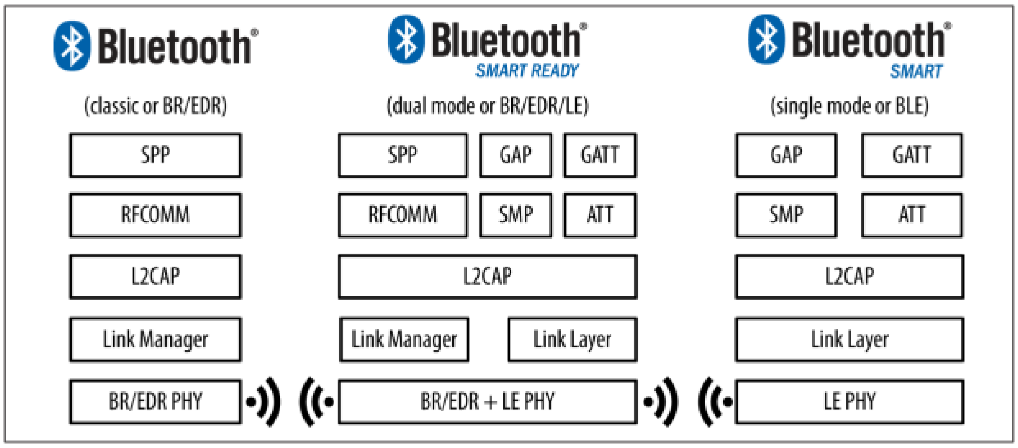


***Figure* 2.7** *Bluetooth device types.*

Three most popular configurations in commercial products are: SoC (system on chip), Dual IC over HCI, Dual IC with connectivity device (Fig. 2.8) [7].

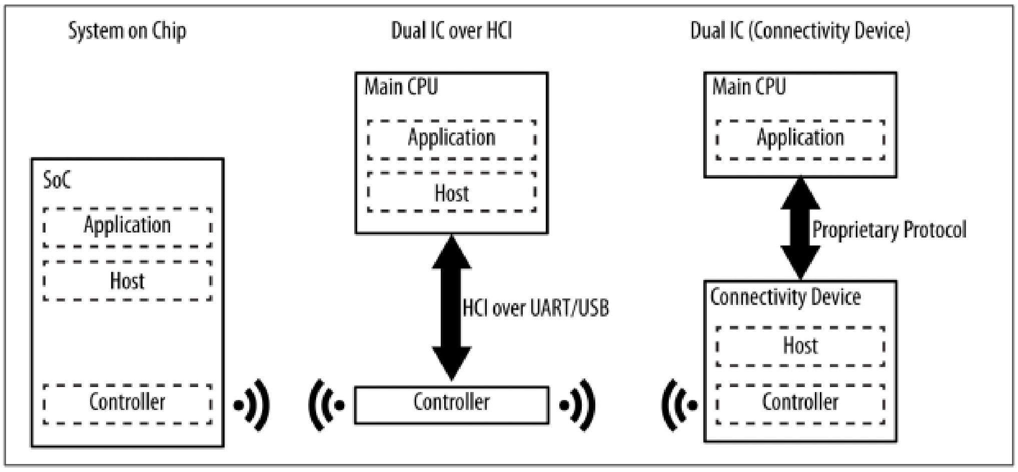


***Figure* 2.8** *BLE hardware configurations.*

- *SoC (system on chip)*: an all-in-one Integrated Circuit (IC) runs the application, the host, and the controller.

- *Dual IC over HCI*: One IC running application and host communicate with the second IC running controller by using Host Controller Interface (HCI) defined by Bluetooth specification.
- *Dual IC with connectivity device*: One IC running application communicate with the second IC running controller by using propietary protocol.

In conclusion, BLE is a low energy consumption device which support coin-cell device. In WSN, BLE is a suitable technology for small and less power consuming device like sensor node. Also, the compatibility with classic Bluetooth and diversity in devices for BLE make it a good choice for WSN applications.

2.2.2 BLE in compare with other WSN technologies

Many standards have been proposed for improving WSN performance. Standardized devices from different manufacturers can work together, allowing the expansion in new areas and applications without depending on vendors. In this part we will consider only the communication standards targeted for WSNs and make comparison between those standards to get the pros and cons of the chosen BLE.

In the list below are some competitive communication standards which are available for coin-cell based applications and WSNs:

- *IEEE 802.15.4*: Low-Rate Wireless Personal Area Network (LR-WPAN) developed for low-complexity, low-cost, low-power communication between inexpensive devices. This is a standard for PHY and MAC layer based on Bluetooth technology. IEEE 802.15.4 has been used as a basis for other standards. Some standards use the whole IEEE 802.15.4 for PHY and MAC layers (ZigBee, 6LoWPAN) while others reuse the PHY layer (WirelessHART, ISA100.11a) [19] [9].
- *ZigBee*: an open specification for low-power wireless networking targeted control and monitoring application. ZigBee defines application layer on top of IEEE 802.15.4 PHY and MAC layers [19] [9].
- *ANT/ANT+*: an open access multicast wireless sensor network technology defined by Dynastream Innovations Inc. Its communication mechanism is based on virtual channels which are defined by operating frequency and message rate parameters. ANT+ is an extension version of ANT with profiles defining data formats and channel parameters. [19]

- *Nike/Nike+*: sport kit equipments designed by Nike Inc. for activity tracker which is capable to communicate with each other and handset devices. Nike/Nike+ use it own protocols to exchange data.
- *IrDA*: Infrared Data Association is a complete set of protocols for infrared. This is a wireless optical communication using point and shoot principle with secure data transfer, Line-of-Sight (LOS) and very low bit error rate (BER)
- *NFC*: use electromagnetic induction to establish radio communication between devices by touching them together or bringing them into proximity. NFC standards are based on existing radio-frequency identification (RFID) standards and cover communication protocols and data exchange format.
- *WiFi*: a local area wireless technology for computer networking using 2.4 GHz UHF and 5 GHz SHF ISM radio bands.

The comparison between BLE and other available wireless communication technologies is based on some major features which have high influence in operating duration and communication range Table 2.2 [17] [16].

Table 2.2 *Communication technologies comparison.*

Parameters	**BLE**	**IEEE**	**ZigBee**	**ANT**	**Nike**	**IrDA**	**NFC**	**WiFi**
Power efficiency	0.153 μW/bit	496.9 μW/bit	185.9 μW/bit	0.71 μW/bit	2.48 μW/bit	11.7 μW/bit	x	0.00525 μW/bit
Range	50 m	100 m	100 m	30 m	10 m	10 cm	5 cm	150 m
Throughput	270 kbps	250 kbps	100 kbps	20 kbps	272 bps	1 Gbps	424 kbps	6 Mbps
Latency	3 - 6 ms	x	20 ms	0 ms	1 s	25 ms	x	1.5 ms
Peak power consumption	12.5 mA	x	40 mA	17 mA	12.3 mA	10.2 mA	116 mA	50 mA

From the comparison result, WiFi has the best performance. However, WiFi requires a very high peak power consumption which means a typical WiFi device can not work with normal coin-cell battery. Normally, WiFi device goes with static power resource (electrical wire) or large size battery (cell phone battery). In addition, WiFi usually has complex protocols for transmitting data in high speed. Few bytes data from sensor node can be encapsulated in hundreds of header bytes when using WiFi as communication mean. For WSN with coin-size sensor nodes, BLE is the most potential technology with very low power consumption, sufficient communication range for deploying in open area, low latency and low peak power consumption.

3. SINGLE NODE SCENARIO

From the comparison between wireless communications, BLE is the first candidate for proposed WSN system. This chapter will go deeply into BLE operation to analyse and suggest detail configuration for new system operation.

3.1 BLE peer-to-peer operation

First of all, we examine BLE's operation through working states of BLE device. Based on host and controller part, there are five major (four active + sleeping) states which a BLE device can has [4]:

- *Stand by (sleeping)*: device does not transmit or receive packets.
- *Advertising*: device broadcasts advertising packets in advertising channels.
- *Scanning*: device scans for advertising package broadcast in advertising channels.
- *Initiating*: *scanner* establishes connection to *advertiser*.
- *Connection*: devices exchange data with each other.

In BLE, there are four operating modes (roles) defined by GAP profile: *peripheral-central (slave-master)*, *broadcaster-observer (advertiser-scanner* [7].

- *Broadcaster (advertiser)*: periodically sends out advertising packets with useful data inside.
- *Observer (scanner)*: only collects data from *broadcaster*.
- *Central (master)*: corresponds to *master* device capable of establishing multiple connection to *slave* devices.

- *Peripheral (slave)*: corresponds to *slave* device capable of using advertising packets for *central* device to find and establish a connection to it.

Corresponding to different operating mode, BLE device has different working states (Fig. 3.1) [4]. *Broadcaster (advertiser)* only has two states: advertising and standby (sleeping) while *peripheral (slave)* has three states advertising, connecting and standby. Correspond to those two operating mode devices are *observer (scaner)* with two states: scanning and sleeping and *central (master)* with four states: scanning, initiating, connecting and standby.

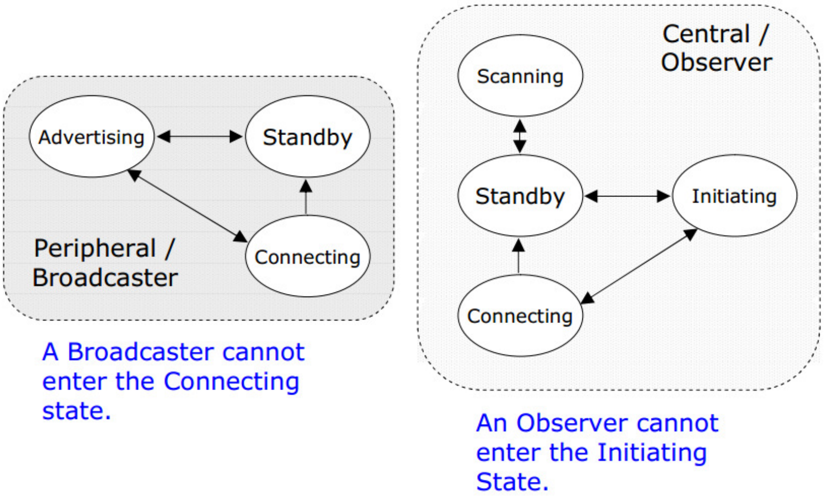


Figure 3.1 *Corresponding states for different BLE operating modes.*

As mentioned above, BLE device usually stays in stand by (sleeping) state in around 90% of duty cycle to get efficient power consumption. Device can wakes up in three ways to change to Advertising state: a period $3-\mu s$ wake up, wake up via sleep timer, wake up on external interrupt. For commercial BLE chip set, the most appropriate way is wake up by sleep timer.

In proposed system, sensor nodes can play a role of BLE *peripheral (slave)* or *broadcaster (advertiser)* which periodically wakes up in predefined schedule and advertises itself. Meanwhile, UAV carries a BLE *central (master)* or *observer (scanner)* device to scan and connect to sensor nodes. Since *central/observer* device is mobile and can recharge energy any time, the lifetime of new system depends mostly on lifetime of *peripheral/advertiser* (sensor node).

To examine lifetime of a single node, this section focus on two most power consuming events in BLE operator: *advertising event* and *connection event*. Fig. 3.2 [8] shows the change from advertising mode to connecting mode correspond to the operation of *advertising event* and *connection event*.

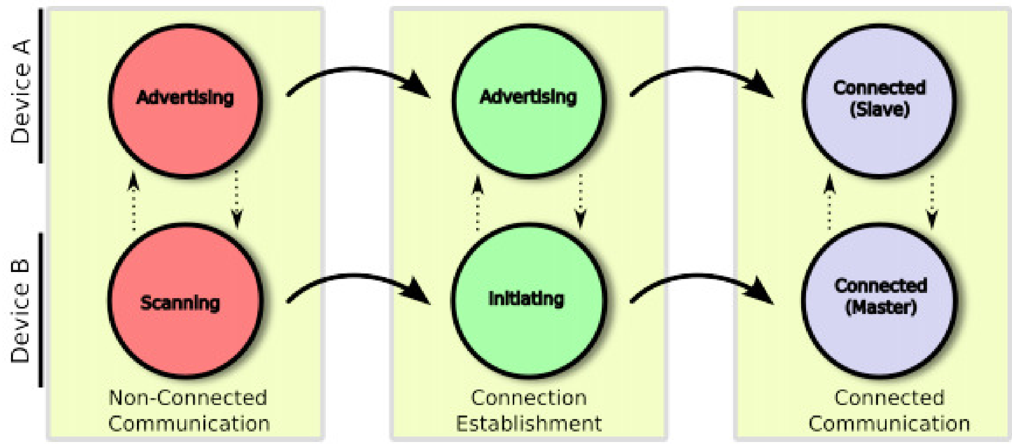


Figure 3.2 *States correspond to* advertising *and* connection event*.*

To exchange data, first, BLE device must discover its neighbors. This can be obtained via advertising process (*advertising event*). Then devices can establish connection and communicate with each other (*connection event*). In case of devices are set as *broadcaster* and *observer* they can get data directly from advertising process without establishing any connection. By far, establishing connection between node is the most appropriate way to exchange data supported in commercial BLE chip set.

There are two ways to discover neighbors by scanning: passive scanning and active scanning. The *peripheral* sends advertising packets within 3 advertising channels (37, 38, and 39) while the *central* scans these channels continuously to discover the *peripheral*. The *central* device can get advertising packages in passive way without responding (passive scanning) or *central* device can get scanning respond package after sending scan-request package (active scanning) (Fig. 3.3) [4].

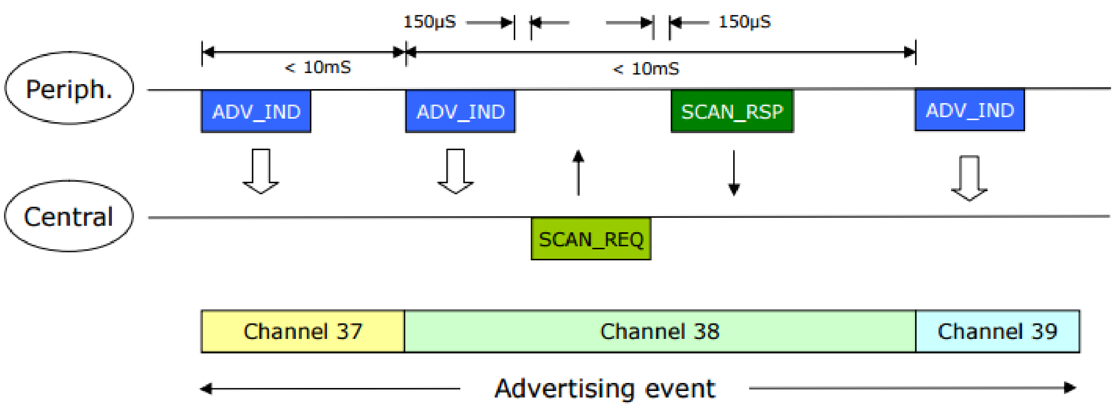


Figure 3.3 *Advertising event.*

The *connection event* operates simpler than *advertising event*. When a *central* discovers a *peripheral*, it can send a connection request with useful information to establish connection. The connection is set right after connection request package is achieved without any acknowledgement from *peripheral* and both devices change to connection state (get into *connection event*) to exchange (data Fig. 3.4) [4].

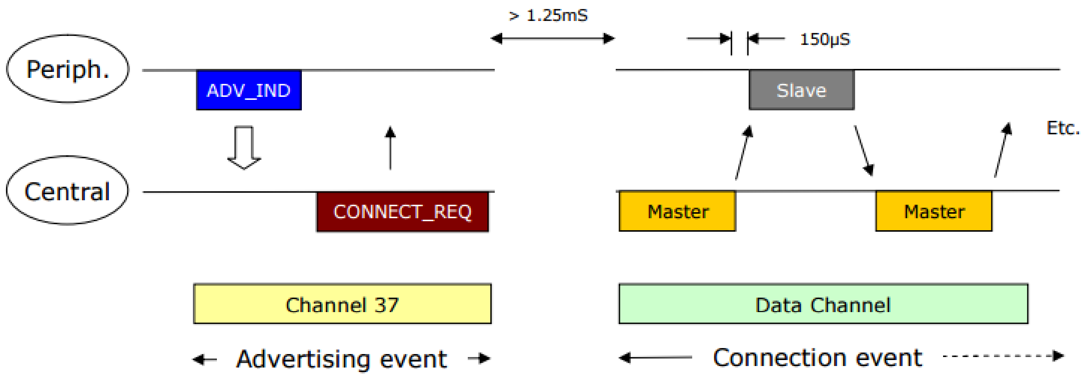


Figure 3.4 *Connection event.*

3.2 Data exchange duration

As illustrated in Fig. 3.4, the duration for data exchange in one transaction between two BLE devices include time for discovering, connecting and transferring data. *Connection duration* T is equal to the sum of *discovering time* T_{dis} and *connection time* T_{con} (Eq. 3.1).

$$T = T_{dis} + T_{con} \tag{3.1}$$

In discovering process, *peripheral* node periodically sends out advertising packets in *advertising interval* T_a while *central* node keeps scanning during *scanning interval* T_s until getting the advertising packets (Fig. 3.5) [8].

Assume that *central* device scans for advertising package continuously and receives advertising package anytime during advertising interval which composed of static interval $T_{a,0}$ ($20ms < T_{a,0} < 10.24s$ [8]) and random time ρ ($0ms < \rho < 10ms$ [8]). Random time ρ is added to keep advertising interval T_a changing randomly so that next advertising package will not be missed. The Discovery event can happen from the first *advertising event* or in the next event therefore *discovering time* T_{dis} is given by Eq. 3.2:

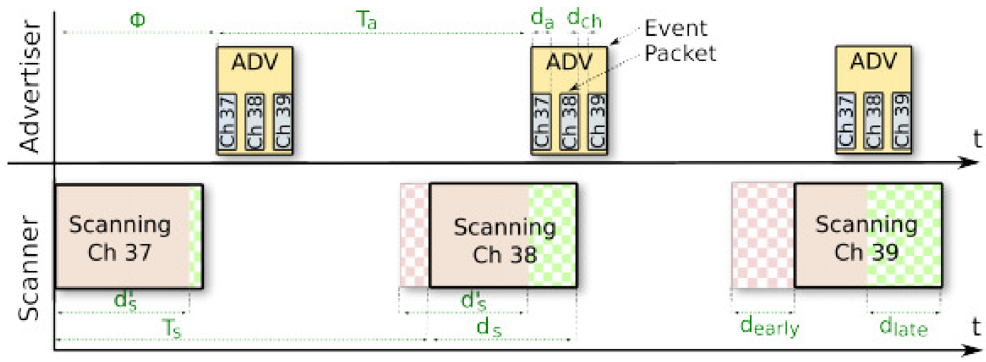


Figure 3.5 *Advertising process.*

$$
\begin{aligned}
d_a < &T_{dis} < T_a + d_a \\
d_a < &T_{dis} < T_{a,0} + \rho + d_a \\
446\mu s < &T_{dis} < 10.250446s
\end{aligned}
\tag{3.2}
$$

where d_a is the time to send the advertising package. The 37-byte advertising package long costs $446\mu s$ and BLE needs at least $446\mu s$ to process *advertising event*.

After discovering neighbors, BLE devices will start to process *connection event*: establish connection and exchange data (Fig. 3.6) [8].

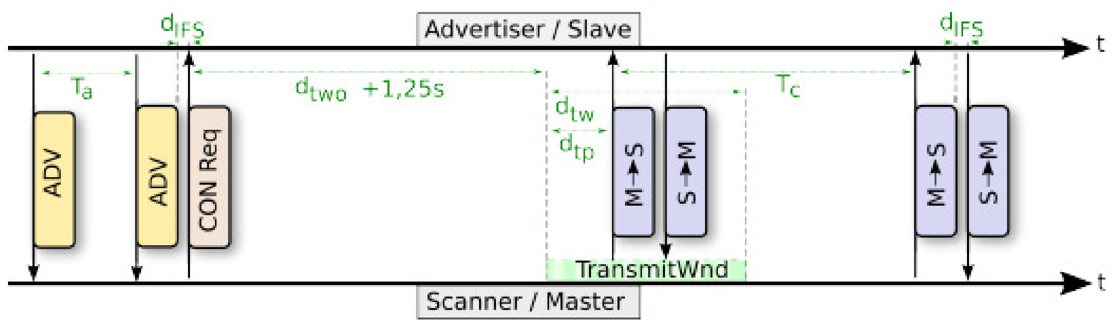


Figure 3.6 *Connection establish flow.*

To assess the connection time during *connection event* we consider a minimum transaction: when connection is established, *peripheral* transfers one data packet to *central* and *central* responses to *peripheral* for acknowledgement. After receiving at least one advertising packet, the *central* sends a connection request packet d_{IFS} ($150\mu s$) time units later. This packet contains two parameters called *transmitWindowOffset* (d_{two}) and *transmitWindow* (d_{tw}) that determine the timing of the connection establishment procedure.

Following Fig. 3.6 we can estimate the connection time T_{con} of one transaction when *central* discovers a *peripheral* and finishes data transfer process in Eq. 3.3.

$$T_{con} = d_{IFS} + d_{two} + 1.25ms + d_{tw} \tag{3.3}$$

where: $0ms < d_{two} < 4s$, $1.25ms < d_{tw} < 10ms$ and the connection duration will be:

$$\begin{aligned} d_{IFS} + 1.25ms < & T_{con} < d_{two} + 1.25ms + d_{tw} \\ 1.4ms < & T_{con} < 4.0114s \end{aligned} \tag{3.4}$$

We assume that, in the new system, UAV carries a *central* which scans for advertising packets continuously and enters the coverage area of *peripheral*. First, *central* has to process the *advertising event* and then handles the *connection event* to exchange data with sensor node (*peripheral*). From Eq. 3.2, Eq. 3.3, Eq. 3.4, the estimated result for data exchange duration is $1.846ms < T < 14.261846s$. In the best case ($T = 1.846ms$), BLE carry *central* device and gets into communication range of *peripheral* (sensor node) during the active time of *peripheral* and gets connection immediately. In the worst case ($T = 14.261846s$), *central* device has to wait for the next *advertising event* to get connection.

3.3 UAV flying height

By using UAV (Unmanned Aerial Vehicle) to collect data from BLE sensor nodes we need to take the height of UAV into account to get the proper and effective flying height for UAV. Since the proposed system is aim at measuring environment parameters for agriculture, the UAV have to fly above the height of usual obstacles in the field (for example trees, etc ..). Another constrain is the flying height have to low enough for UAV to get into coverage area of *peripheral* node long enough to exchange data. The time limitation is the worst case for exchanging data in BLE peer-to-peer data transaction which mean UAV have to fly in sensor node communication range more than $14.261846s$.

To calculate proper flying height of UAV we consider some parameters based on specification of UAV and BLE:

- UAV speed (v): 10m/s(average) and 15m/s (maximum)

- BLE communication range (R) is from $30m$ (with $Tx = 0dBm$ and $Rx = -70dBm$) to $100m$ (with $Tx = 10dBm$ and $Rx = -90dBm$)
- Data exchange time (T_{con}): $1.846ms$ to $14.261846s$

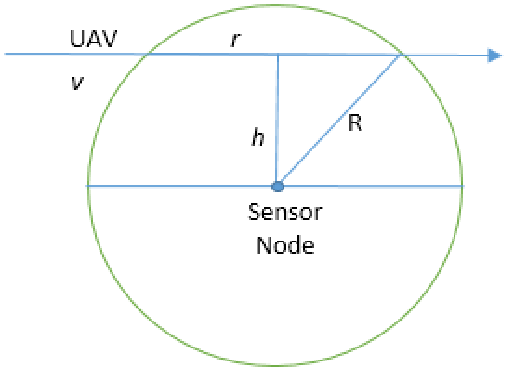


Figure 3.7 *UAV flying height.*

The flying height of UAV is related to BLE communication range R (Fig. 3.7). From the maximum communication range, the maximum relative altitude h of UAV from sensor node can be derived from equation Eq. 3.5.

$$h = \sqrt{R^2 - (\frac{vT_{con}}{2})^2} \tag{3.5}$$

where v is UAV velocity (the average value is $10m/s$ and the maximum value is $15m/s$)

The required UAV flying height with different UAV speeds and BLE communication ranges is shown in Table 3.1. To ensure calculated flying height is suitable with any cases, the result is calculated for the worst case when UAV need at least $14.261846s$ to exchange data with sensor node.

Table 3.1 *UAV flying height (h).*

	$v = 10m/s$	$v = 15m/s$
$R = 30m$	N/A	N/A
$R = 100m$	<70.107 m	N/A

As can be seen from Table 3.1, the BLE communication range of $30m$ is not sufficient for using UAV to collect data. Therefore, the suggested configuration for proposed system is: BLE communication range is set at $100m$ ($Tx = 10dBm$ and

$Rx = -90dBm$). In this case, if UAV flies at the average speed of $10m/s(36km/h)$, the flying height should be under $70.107m$. Since the proposed system is used for agriculture monitoring, the best flying height should be over the height of trees ($10m$ to $30m$).

Apparently, when we keep UAV flying speed slow, UAV can have enough time to exchange data with sensor node but the coverage range of UAV is decreased. To increase UAV velocity, we need to decrease flying height. From the relation of UAV height, flying speed and connection time shown in Fig. 3.8, the most optimal flying speed of UAV is $13m/s$ at flying height from $10m$ to $30m$.

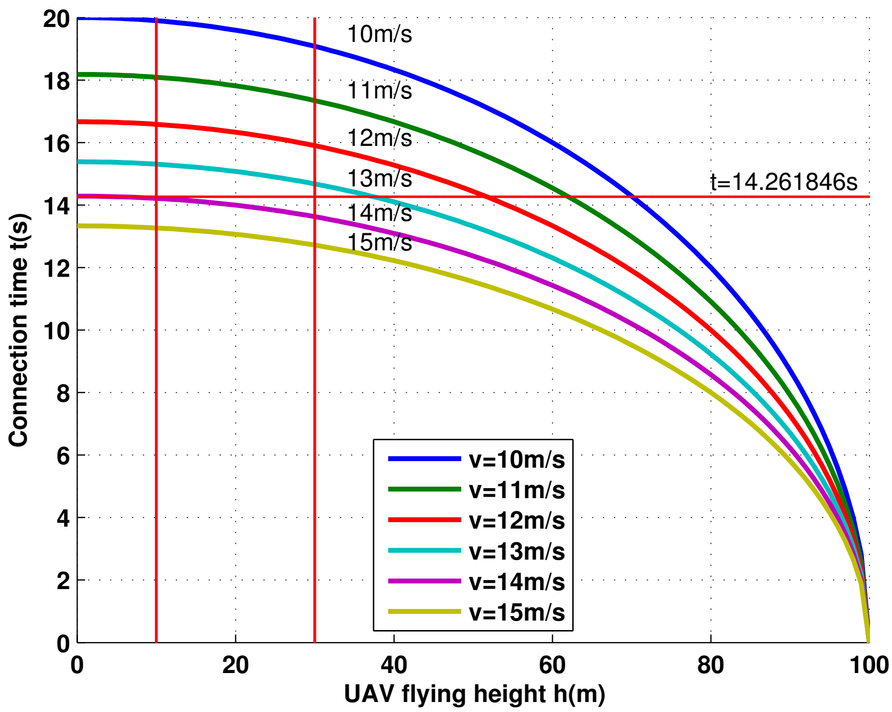


Figure 3.8 *Relation between UAV flying height and data exchange time in different UAV speed.*

3.4 Power transmission requirement

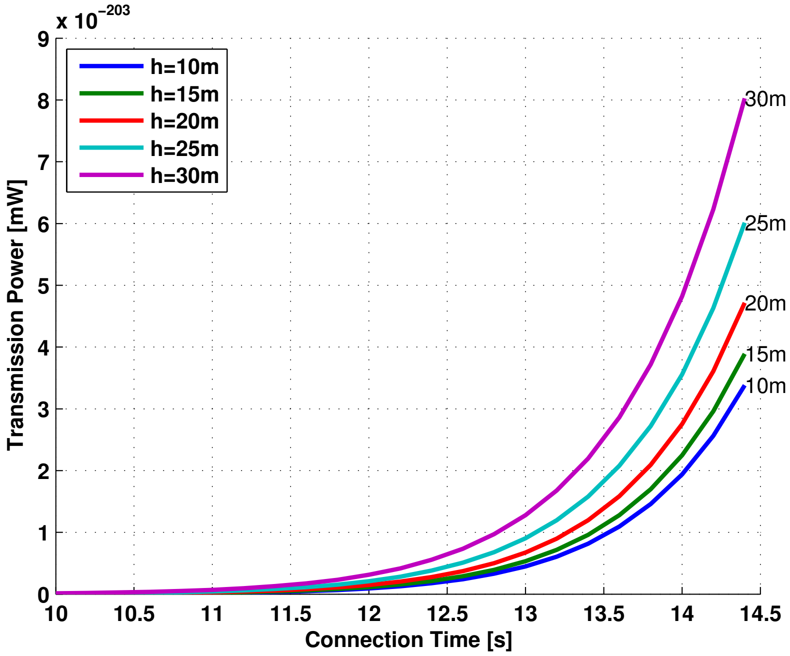
When UAV passes monitoring area, the distance between UAV (*central*) and sensor node (*peripheral*) will vary between the nearest point (equals to UAV flying height h) to the farthest point (equal to sensor node communication range R). To guarantee the connection between UAV and sensor node, we need to keep transmission power as strong as possible to reach the limited distance for establishing connection and exchanging data.

From the suggested configuration for UAV (the flying height is $10m$ to $30m$ and the flying speed is $13m/s$), we calculate the required power transmission level of sensor node to adapt with UAV configuration. Since the proposed system is applied for monitoring flat and having line-of-sight crop field, the Free Space Path Lost (FSPL) propagation model is applied for calculating power transmission. Using Friis equation to derive needed transmission power (Eq. 3.6):

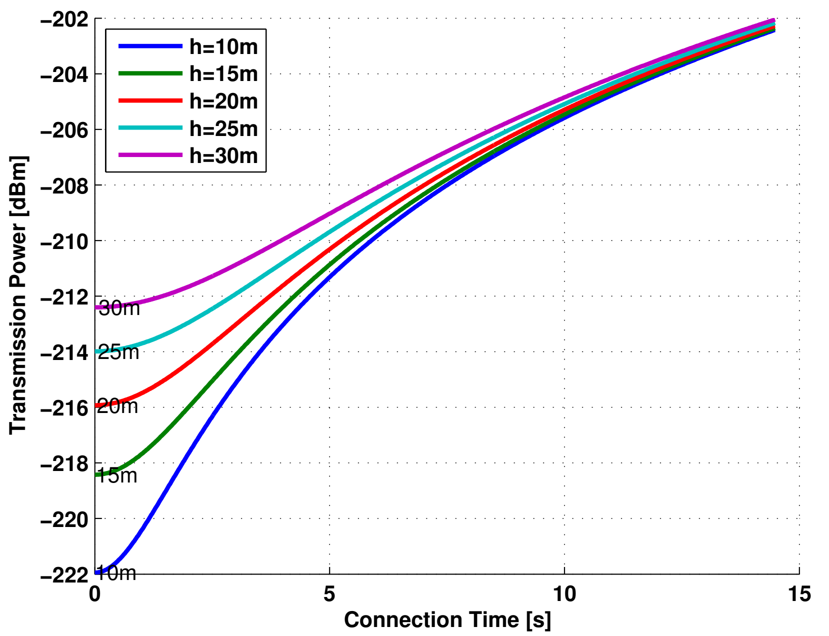
$$\begin{aligned} P_r &= P_t + G_t + G_r - 20\log_{10} d - 20\log_{10} f + 147.55 \\ P_t &= P_r - G_t - G_r + 20\log_{10} d + 20\log_{10} f - 147.55 \end{aligned} \tag{3.6}$$

where: P_r ($-90dBm$) and P_t are transmission power at receiver and transmitter respectively, G_t and G_r are antenna gain ($6dBi$), d is transmission range in km and f is transmission frequency ($2400MHz$).

Fig. 3.9 represents the relation of transmission power and connection time when UAV flying height varies from $10m$ to $30m$. The required transmission power in proposed system is quite low from $-221.946dBm$ to $-202.27dBm$ compared to BLE standard power transmission ($-20dBm$ to $10dBm$ in Table 2.1). Although the most optimal power transmission set for sensor node is ten times less than default configuration, we suggest to keep it at BLE standard level ($Tx = 10dBm$ and $Rx = -90dBm$) to guarantee the performance of system.



(a) Power consumption in mW.



(b) Power consumption in dBm.

Figure 3.9 *Transmission Power correspond to required connection time in different flying height of UAV.*

4. COMPARISON WITH MODERN WSN

This chapter estimates proposed system in network lifetime, number of nodes for covering and keeping connectivity. Also, some comparisons are made in the same aspects between new system and the other available system models.

4.1 Network lifetime

For estimating the lifetime of new system, power consumption of a single data exchange transaction is considered with the simplest process. The process includes two major events: *advertising event* in passive mode and *connection event*. In the best case when sensor node (*peripheral*) wakes up and is discovered by UAV (*central*) after the first advertising packet, the *connection event* is established. Only one data packet is transmitted from sensor node to UAV and one control packet is responded from UAV to sensor node (four packages are exchanged in total) (Fig. 4.1).

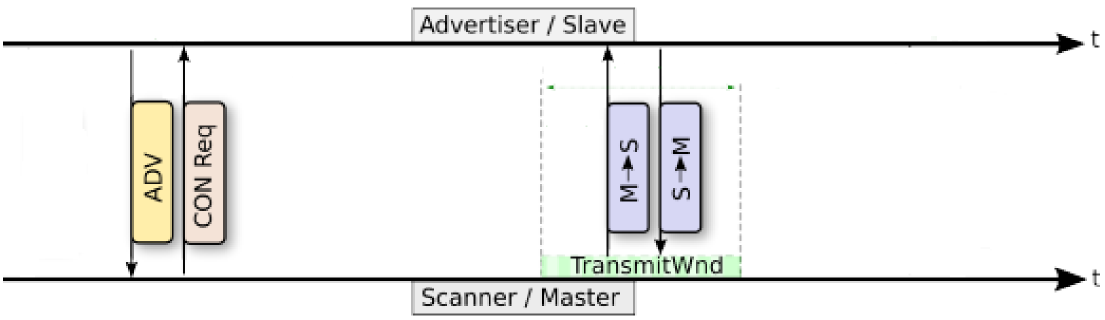


Figure 4.1 *Data exchange flow.*

The power consumption of data exchange process is calculated based on energy consumption of *advertising event* and *connection event* in Physical layer. The measurements are made on CC254x System-on-Chip family produced by Texas Instrument.

Major equation applied for calculating power (P) is given in Eq. 4.1

$$P = \frac{E}{t} = \frac{\sum E}{\sum t} = \frac{\sum_i U_i I_i t_i}{\sum_i t_i} \tag{4.1}$$

The radio states of *advertising event* is shown in the bellow Fig. 4.2 [13] and Table 4.1 [13]. In *advertising event* states, BLE device will send advertising packages (Tx) and listen for scan requests (Rx) on both three advertising channels (ch37,38,39). These states are illustrated by peaks on radio waveform. Before going to advertising activities, the chip goes through several states represented in Table 4.1.

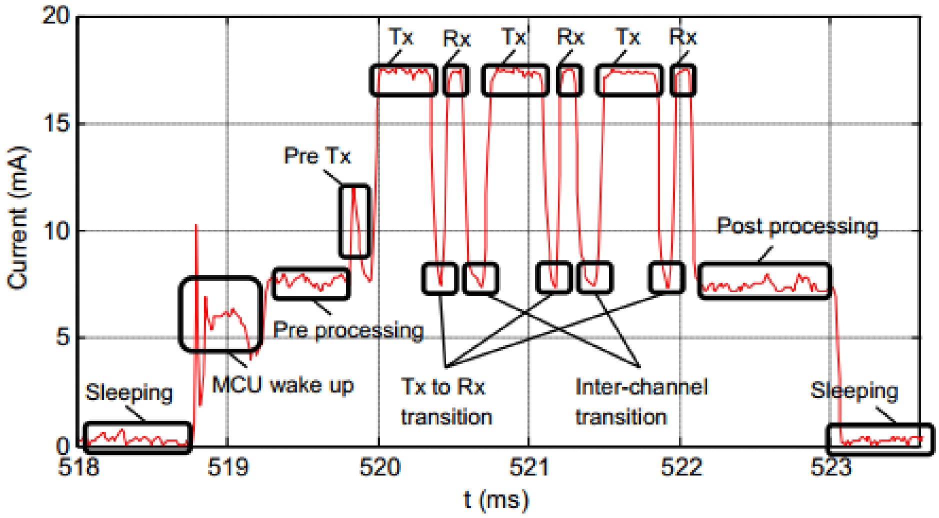


Figure 4.2 *Advertising event waveform.*

Table 4.1 *Time and measurement current of* advertising event*'s sates.*

Sate No	**Explaination**	**Time**(μs)	**Current**(mA)
State 1	wake-up	400	6.0
State 2	pre-processing	600	7.4
State 3	pre-Tx	200	10.0
State 4	Tx on ch37	380	17.5
State 5	Rx-to-Tx	105	7.4
State 6	Rx on ch37	115	17.5
State 7	Inter-ch37 & 38	150	7.4
State 8	Tx on ch38	380	17.5
State 9	Rx-to-Tx	105	7.4
State 10	Rx on ch38	115	17.5
State 11	Inter-ch38 & 39	150	7.4
State 12	Tx on ch39	380	17.5
State 13	Rx-to-Tx	105	7.4
State 14	Rx on ch39	115	17.5
State 15	post-processing	950	7.4

The radio states of *connection event* shown in the bellow Fig. 4.3 [6] and Table 4.2 [6] represent a single transaction with one data package is received (Rx) and one response package is sent (Tx). Other states of *connection event* are represented in Table 4.2

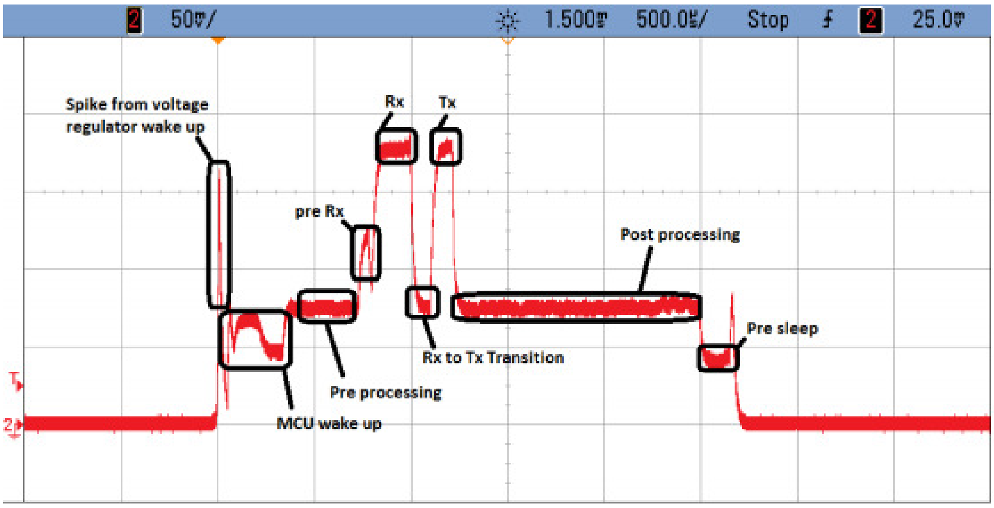


Figure 4.3 *Connection event waveform.*

Table 4.2 *Time and measurement current of* connection event*'s states.*

Sate No	Explanation	Time(μs)	Current(mA)
State 1	wake-up	400	6.0
State 2	pre-processing	340	7.4
State 3	pre-Rx	80	11.0
State 4	Rx	190	17.5
State 5	Rx-to-Tx	105	7.4
State 6	Tx	115	17.5
State 7	post-processing	1280	7.4
State 8	pre-sleep	160	4.1

By applying equation Eq. 4.1 for *advertising event* and *connection event* we get the power consumption in each event and for the whole process (P) in Eq. 4.2, 4.3, 4.4:

$$P_{ad} = \frac{\sum_i U_i I_i t_i}{\sum_i t_i} = \frac{U \sum_i I_i t_i}{\sum_i t_i} = 32.759(mW) \tag{4.2}$$

$$P_{con} = \frac{\sum_i U_i I_i t_i}{\sum_i t_i} = \frac{U \sum_i I_i t_i}{\sum_i t_i} = 24.762(mW) \tag{4.3}$$

$$P = P_{ad} + P_{con} = 32.759 + 24.762 = 57.521(mW) \tag{4.4}$$

From Eq. 4.4, a BLE device will consume $57.521mW$ or $19.173mA$ in $6.92ms$ for one transaction. It costs $32.759mW$ or $10.919mA$ in $4.85ms$ for *advertising event* and $24.762mW$ or $8.254mA$ in $2.67ms$ for *connection event*. By assuming that sensor nodes use a typical coin-cell battery CR2032 (voltage $3.0V$, capacity $225mAh$), it can work continuously in $225/10.919 = 20.605hours$. If we set the device to wake up periodically in each $10s$, it can last for $2020.104days$ (around $5.53years$).

Take a normal routing WSN system with cluster-tree topology shown on Fig. 1.4 (used on TUTWSN) in comparison with proposed system. Nodes stay connected with each others and all sensors data will be routed to Gateway via *sink-nodes*. Therefore, *sink-node* (or *head-node*) will be the first node to be run out of battery. The life time of WSN depends on the duration of *sink-nodes* while the duration of *sink-nodes* depend on the number of *sub-nodes*, number of *sink-nodes* connected to gateway, connection interval (time from one *connection event* to the next *connection event* of node).

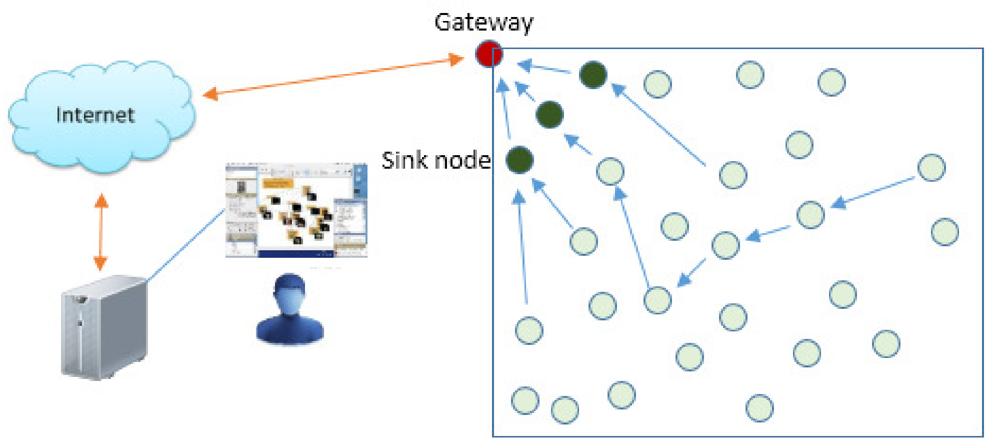


Figure 4.4 *Routing WSN.*

Denote: M is the number of *sub-nodes* $(100 - 1000nodes)$, N is the number of *sink-nodes* that directly connect to Gateway $(1 - 10nodes)$, d_t is connection interval $(3 - 10s)$. The lifetime of routing WNS is given in Eq. 4.5.

$$T_f = \frac{T_c}{T_d}.d_t = \frac{T_c.N.d_t}{t_c.M} \tag{4.5}$$

Assume that the routing WSN uses the same communication technology (BLE), we can calculate the lifetime of routing WSN based on BLE *connection event* which power consumption is $24.762mW$ ($8.254mA$ over $2.67ms$). The lifetime of routing WSN is represented in Fig. 4.5.

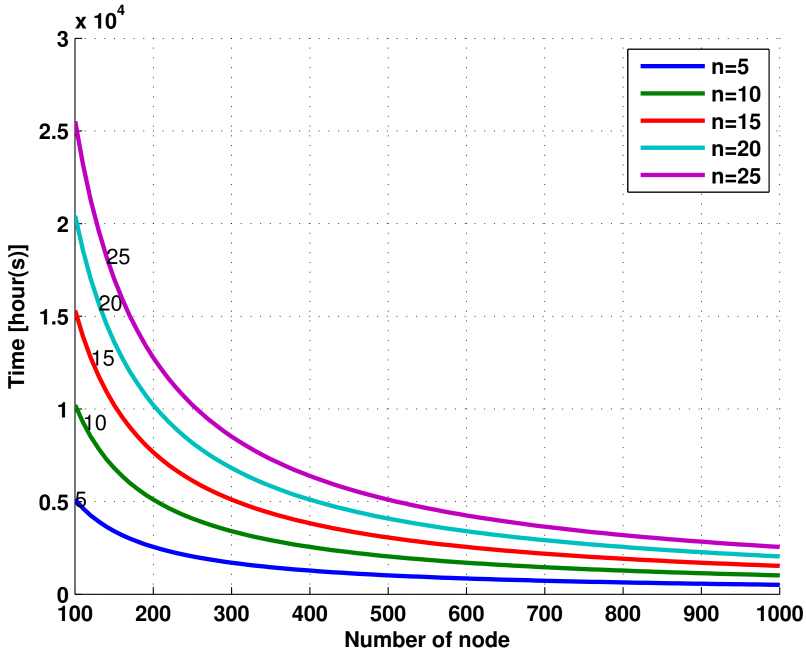


Figure 4.5 *Routing WSN lifetime response to number of Sink node*

As we can see in Fig. 4.5, the maximum lifetime of a normal routing WSN with the same communication technology is $2552.3886hours$ which is 18 times smaller than $48482.496hours$ of proposed WSN.

4.2 Coverage

This section will compare the number of nodes needed for covering monitoring area in proposed WSN system and modern WSN system. The estimation is based on stochastic-based method and assets for different areas. The formulation can be applied for network model where sensors can be deployed according to any distribution, sensors can have a sensing area of any arbitrary shapes, sensors can have heterogeneous sensing areas [11].

Denote $A_0(F_0, L_0)$ is the monitoring area with perimeter L_0 and area F_0. Assume that N sensors are distributed according to $K(A_0)$ distribution over sensing area (A_0) in a way that they cover parts of interesting field. Each sensor has a sensing field $A_i(F_i, L_i)$,$(i = 1 \ldots N)$ where L_i, F_i are the perimeter and area of sensing area respectively.

Based on the kinematic density and motion of sensor nodes, the stochastic model of coverage area is given by two models:

- The fraction of A_0 that is not covered by any sensor when N sensors are randomly deployed or the probability that monitoring area A_0 is not 100% coverage.
- The probability that a randomly selected point of A_0 is covered by at least $k(k \geq 1)$ sensor(s).

The fraction of A_0 that is not covered by any sensors when N sensors are randomly deployed is given by Eq. 4.6 [11].

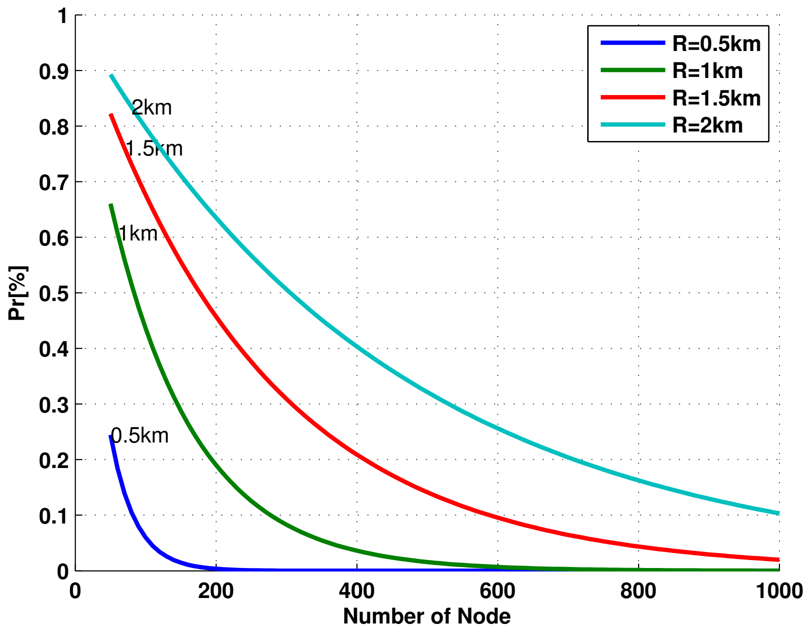
$$p(S=0) = \prod_{i=1}^{N} \frac{2\pi F_0 + L_0 L_i}{2\pi(F_0 + F_i) + L_0 L_i} \tag{4.6}$$

The probability that a randomly selected point of A_0 is covered by at least k sensors is given by Eq. 4.7 [11].

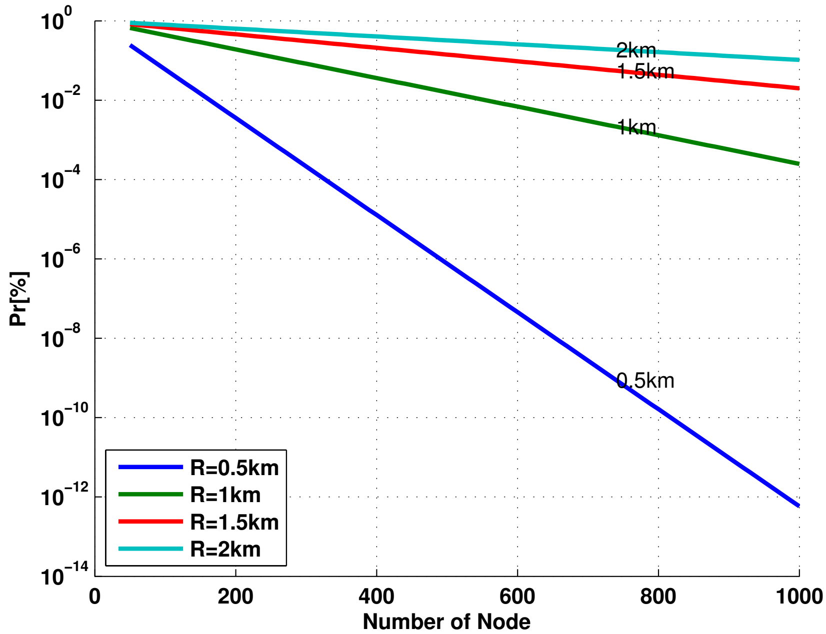
$$\begin{aligned} p(S=0) &= \frac{\sum_i^{\binom{N}{h}} (\prod_{j=1}^{N}(2\pi F_{T_{i,j}}) \prod_{z=1}^{N-h} \Theta(i,z))}{\prod_{r=1}^{N}(2\pi(F_0+F_r)+L_0 L_r)} \\ \Theta(i,z) &= 2\pi F_0 + L_0 L_{G_{i,z}} \\ p(S \geq 1) &= 1 - \sum_{h=1}^{k-1} p(S=h) \\ &= 1 - \frac{\sum_i^{\binom{N}{h}} (\prod_{j=1}^{N}(2\pi F_{T_{i,j}}) \prod_{z=1}^{N-h} \Theta(i,z))}{\prod_{r=1}^{N}(2\pi(F_0+F_r)+L_0 L_r)} \end{aligned} \tag{4.7}$$

where $T_{i,j}$ is a matrix in which each row i is a k-permutation of $[1 \ldots N]$, $G_{i,z}$ is a matrix in which each row i contains the elements of $[1 \ldots N]$ that do not appear in the $i^t h$ row of $T_{i,z}$.

Fig. 4.6 and 4.7 are simulation results for two coverage models with node communication range is $100m$ and monitoring area radius are $1km$ and $2km$. From both models, the number of nodes needed for covering 95% of interesting area whose radius is $1km$ are 365 nodes and 510 nodes respectively. The node density for covering are $117 nodes/km^2$ and $163 nodes/km^2$.

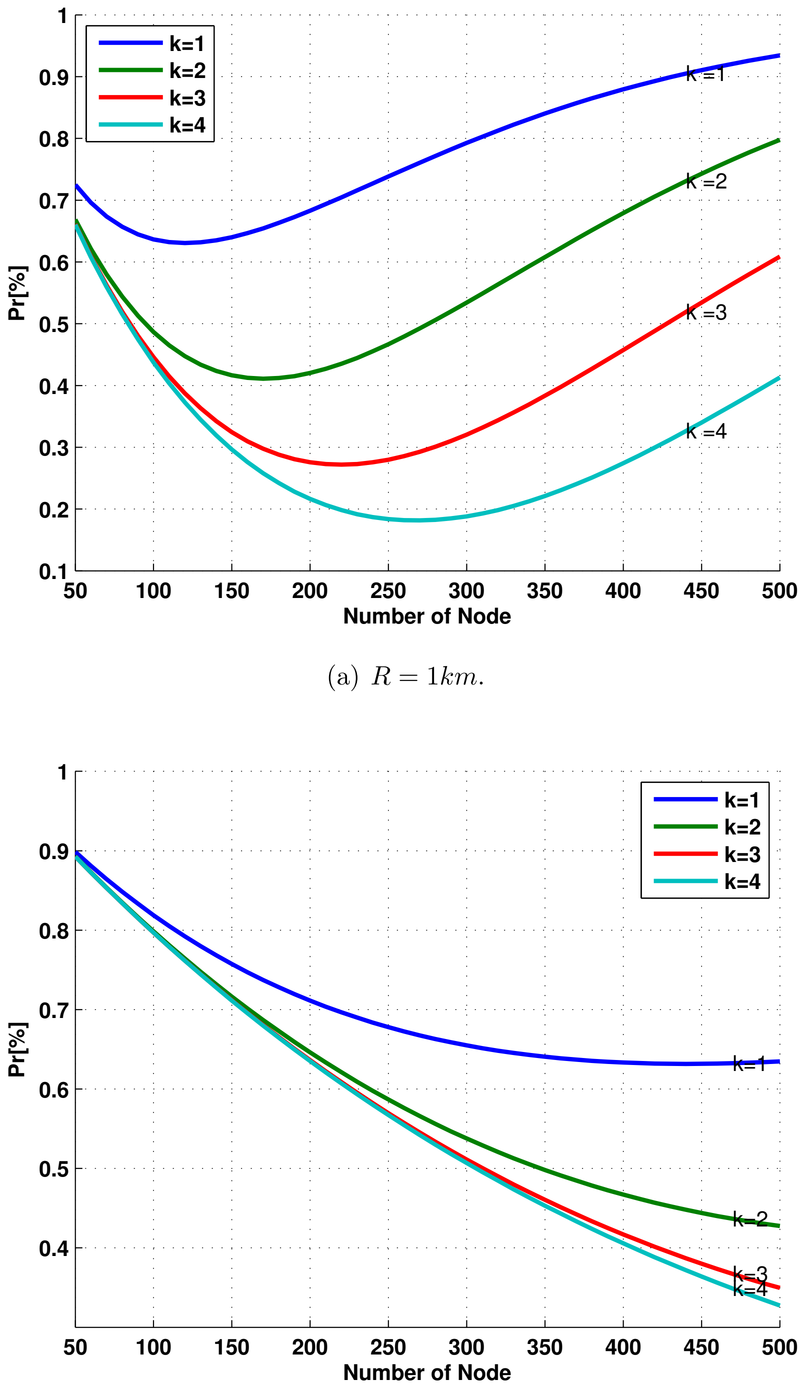


(a) Linear scale.



(b) Log scale.

Figure 4.6 *Probability of monitoring area is not 100% covered*



(a) $R = 1km$.

(b) $R = 2km$.

Figure 4.7 *Probability of any arbitrary point of A0 covered by at least k sensors on disk field area.*

4.3 Connectivity

In routing WSN, we have to keep a large number of sensor nodes to cover 100% of sensing area and to keep nodes connect to each other.

Proposed WNS does not require nodes to connect to each other, the number of deployed nodes in the new system is for covering task ($117 nodes/km^2$ to $163 nodes/km^2$). While in routing WSN, nodes also have to maintain connectivity with each other and need more nodes than for covering task in the same sensing area. In this section, we calculate the number of nodes deployed on monitoring area so that network is at least 1-connected. Which means finding the number of nodes so that every arbitrary source and destination can have at least one path to connect to each other. The connectivity task is computed based on stochastic-based algorithm.

The connectivity probability of routing WNS is assessed based on a approximation method of Random Waypoint Mobility (RWP) model, which is the most popular mobility models used in performance studies of ad hoc networks. We study k-connectivity in the case where the distribution of the nodes is restricted to a unit disk area. In particular, we are going to find the probability that a network with n nodes is k-connected at an arbitrary point of time.

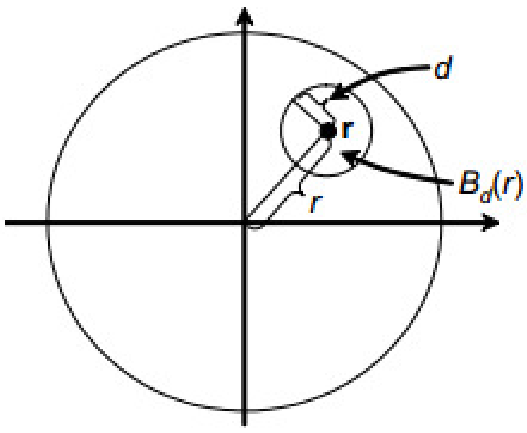


Figure 4.8 *Illustration of notation.*

Denote the probability that a network with n nodes is k-connected is $C_{n;k}(d)$, where d is the transmission range. Due to the assumed circular shape of monitoring area A_0, the distribution of the node location depends only on the distance r from the center, as given by Eq. 4.8. The coverage area of each node is also assumed to be circular with a radius of d and is denoted by $B_d(r)$, see Fig. 4.8. Note that in principle, the domain of distributing area can be any convex region, therefore our general result will holds and the approximations also hold for any convex region.

$$f(r) = \frac{2(1-r^2)}{C} \int_0^{\pi} \sqrt{1 - r^2 \cos^2 \phi d\phi} \tag{4.8}$$

Denote n is the number of nodes distribute in monitoring area, and k is the number of neighbors of arbitrary node at any point. The probability that an arbitrary node has at least k neighbors is given by Eq. 4.9 [10] and the probability that a network with n nodes is k-connected at an arbitrary point of time is given in Eq. 4.10 [10]. K-connected network means from any source and destination pairs there are always k paths to connect between them.

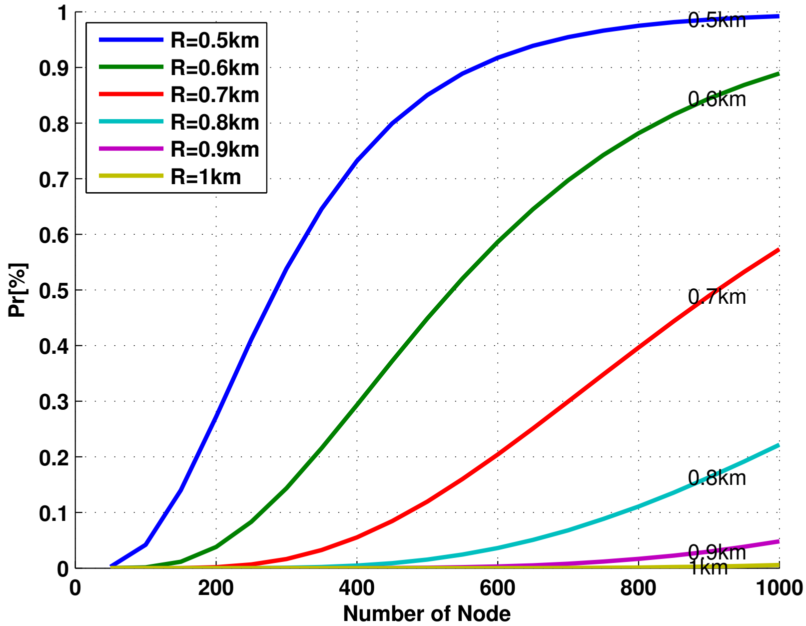
$$Q_{n,k}(d) = 2\pi \int_0^1 rf(r)(1 - \sum_{i=0}^{k-1} \binom{n-1}{i} .p(r,d)^i.(1-p(r,d)^{n-1-i}))dr \tag{4.9}$$

$$C_{n,k}(d) = P\{n \quad nodes \quad are \quad k-connected\} \approx (Q_{n,k}(d))^n \tag{4.10}$$

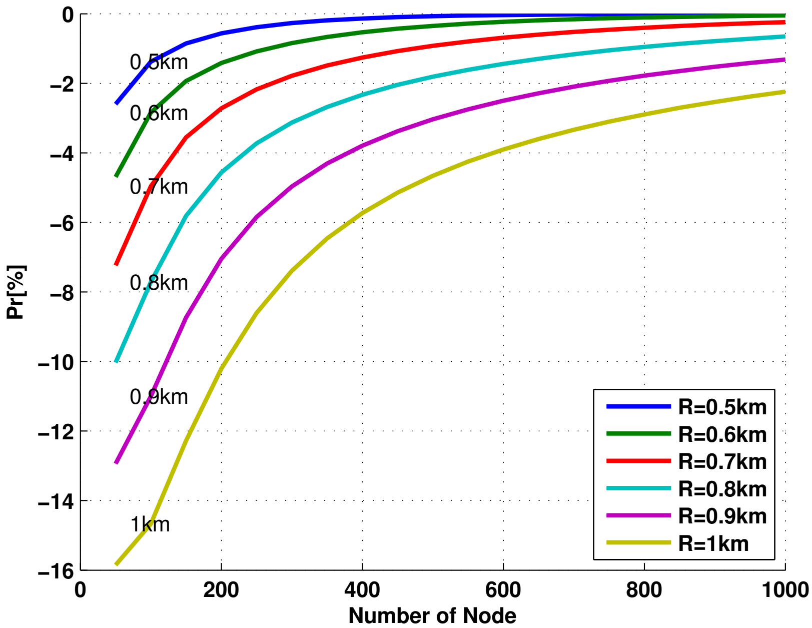
where $p(r,d)$ is the probability that a given node is within communication range of any arbitrary node in monitoring area. $p(r,d)$ is computed numerically in Appendix A.

Simulation result for probability of WSN is 1-connected with $n(50-1000)$ nodes on disk field area with radius $R(0.5-1km)$ in linear and log scale is represented in Fig. 4.9.

It is obvious from Fig. 4.9 that a routing WSN requires much more nodes than the proposed system for keeping connectivity. In proposed WSN, the density of required node is from $117nodes/km^2$ to $163nodes/km^2$ while in routing WSN this number goes to approximately $1000nodes/km^2$, 6-8 times larger.



(a) Linear scale.



(b) Log scale.

Figure 4.9 *Probability WSN is at least 1-connected in disk field R[km].*

5. CONCLUSIONS

This thesis has proposed a new way for collecting distributed data in Wireless Sensor Network (WSN). Two key technologies, Bluetooth Low Energy (BLE) and Unmanned Aerial Vehical (UAV) are examined to apply in new WSN system. New technologies pros and cons are investigated to propose suitable configurations. A single node scenario is analysed including configuration suggestion for the new system. Lastly, comparison between proposed system with normal routing system is made on network lifetime, coverage and connectivity requirements.

The reasons for choosing UAV and BLE technologies for proposed system is discussed in Chapter 2. The concordance of BLE and UAV for WSN is proved by compatible technical specification. Using UAV in collecting data of WSN can avoid routing and resource allocation problems. UAV flexibility also can help to deploy sensor network and collecting data in area which is difficult to deploy wire and mass network such as in the mountain or in the forest. Additionally, comparisons between BLE with other communication technologies showed the advantages of BLE in transferring distributed data and supporting coin-cell based devices. This also proves the feasibility of new system to be deployed in commercial product.

In Chapter 3, a deeper analysis in BLE communication is made on single node scenario. BLE operation is analyzed on two major events: *advertising event* and *connection event*. The power consumptions of these two events are examined through radio states of CC245x family SoC from Texas Instrument. This study points out the average power consumption of a BLE device in a single duty cycle and the needed data exchange time. From the power consumption coefficients, the required transmission power is derived and also a suggested configuration for UAV flying height is achieved.

Finally, in chapter 4, the comparisons between proposed system with routing system on network lifetime, number of required node for keeping coverage and connectivity is made based on stochastic method which is independent with network models. It can be seen from the simulation result that proposed system is much more better than routing WSN and can be a competitive candidate in WSN.

The new system is proposed for agriculture application for monitoring crop field in a large area. The monitored environmental parameters in crop field do not require instant updated data (can be measured periodically) but require long lasting devices with least maintenance effort. These application features makes proposed system become the most potential candidate because of the long working time and wide covering ability.

Since this proposed system is still in initial state, there are lots of further researches needed to apply it in real life. But the results in this thesis have shown a very high potential that such system can be deployed. This thesis work also points out that technologies is on the trend to merge and converge for better solutions and better life.

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APPENDIX A: PROBABILITY OF FINDING A NODE INSIDE A GIVEN AREA

An algorithm for computing $p(r, d)$, the probability of finding a node inside a disk field with a radius d at the distance of r from the origin (Fig. 1), is given in Algorithm 1 and 2.

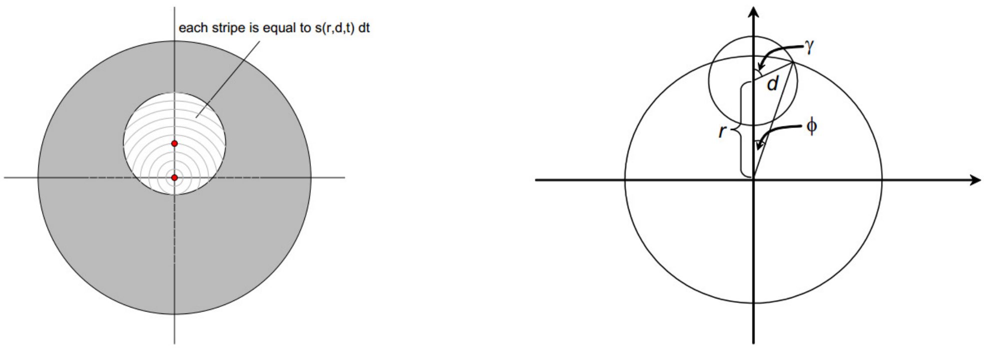

Figure 1 *Represent of Algorithm 1.*

Algorithm 1 Function $s(r, d, t)$

if $t \leq 0$ *or* $t \leq d - r$ **then**
$\theta = 2\pi$
else
$A = d/t$
$B = r/t$
$\theta = 2(\pi/2 - \arcsin((1 + B^2 - A^2)/(2B)))$
end if
$return \quad (1/C).\theta.t.h(t)$

Algorithm 2 Function $p(r, d)$

$t_0 = max\{0, r - d\}$
$t_1 = min\{1, r + d\}$
if $d > r$ **then**
$x = \int_{t_0}^{d-r} s(r, d, t)dt + \int_{d-r}^{t_1} s(r, d, t)dt$
esle
$x = \int_{t_0}^{t_1} s(r, d, t)dt$

where $h(t) = 2(1 - r^2 \int_0^{\pi} \sqrt{1 - r^2 \cos^2 \phi d\phi})$